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UNIVERSITY OF SOUTHERN CALIFORNIA

CONSOLIDATED SEMIANNUAL PROGRESS REPORT

NO. 15

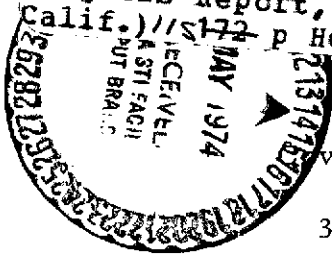
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Covering Research Activity During the Period

30 September 1971 through 1 April 1972

ELECTRONIC SCIENCES LABORATORY



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CONSOLIDATED SEMIANNUAL PROGRESS REPORT

NO. 15

Covering Research Activity During the Period

30 September 1971 through 1 April 1972

Prepared By
The
Electronic Sciences Laboratory
of the
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SUMMARY AND ACKNOWLEDGEMENT

This report presents [a summary of the research program in the broad field of electronics] conducted during the past six months by the Electronic Sciences Laboratory, University of Southern California. The program includes research in solid state materials, semiconductors and devices, quantum electronics, plasmas, applied electromagnetics, electrical engineering systems to include control, communication, computer and power systems, biomedical engineering and mathematical biosciences.

The contents contain summary reports for each research project wherein the work is very briefly described to include recent progress and publications. Readers interested in more detail and publications should contact the principal investigator or author referenced in the summary report.

The overall program is supported by a variety of agencies including the National Science Foundation, the National Aeronautics and Space Administration, the Department of Health Education and Welfare, the Atomic Energy Commission, the California Institute of Technology, the City of Los Angeles Department of Water and Power, the National Association of Corrosion Engineers and the various agencies of the Department of Defense to include the Joint Services Electronics Program. The sponsors of each project are acknowledged in each project summary contained in this report.

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1. SOLID STATE

1.1 MATERIALS AND SEMICONDUCTORS

1.1.1 Urate Crystal Nucleation and Growth in Relation to Gout and Calculi

GK-17042, National Science Foundation

W. R. Wilcox, A. Khalaf, M. Lin and K. Chen

Objective:

To gain understanding of factors influencing crystallization of monosodium urate, particularly in its relationship to gouty arthritis.

Approach:

Nucleation and solubility determinations are being made using a microscope hot stage. Impurity incorporation during crystallization is being studied by chemical analysis. The crystal structure of uric acid is being determined. Solubility and nucleation is being analyzed theoretically.

Recent Progress:

The influence of a variety of soluble additives on solubility and nucleation of sodium urate have been determined. For example, calcium ion was found to greatly enhance nucleation. As pH decreased from 7.3 to 6.5 nucleation increased. Nucleation was easier when 5 vol. % of synovial fluid from a gout patient was added than when fluid from a rheumatoid arthritis patient was added. Cupric ion altered the absorption spectra of urate. X-ray diffraction peak intensity diminished as crystallization rate increased. The infrared spectra of rapidly crystallized "amorphous" urate was identical to slowly crystallized crystalline urate.

References and Recent Publications

1. W. R. Wilcox, A. Khalaf, A. Weinberger, I. Kippen and J. R. Klinenberg, "The Solubility of Uric Acid and Monosodium Urate", J. Med. Biological Eng. (in press).
2. W. R. Wilcox, "Crystallization Flow", J. Crystal Growth 12, 93 (1972).

3. A. A. Khalaf and W. R. Wilcox, "Nucleation of Sodium Urate in Relation to Gouty Arthritis", 24th ACEMB, Las Vegas, Oct. 31 - Nov. 4, 1971.

1.1.2 Corrosive Effects of Smog

National Association of Corrosion Engineers

W. R. Wilcox, T. Shon

Objective:

To investigate the influence of smog on metallic corrosion, especially the mechanism by which ozone influences corrosion.

Approach:

Potentiostatic and ellipsometric measurements are being made during exposure of metals to ozone in concentrations typical of smog.

Recent Progress:

Having shown that ozone does influence corrosion, an apparatus is now being set up to do potentiostatic measurements in order to investigate the mechanism.

References and Recent Publications:

1. "The Influence of Ozone on Corrosion", National Meeting of NACE, St. Louis (March 1972).

1.1.3 New Methods for Growth and Characterization of GaAs and Mixed III-V Semiconductor Crystals

DAHC-15-71-G6, Advanced Research Projects Agency (DOD)

W. R. Wilcox, C. Chang, V. Yip, V. Kuo, A. Esquivel,
S. Sen, E. Johnson, P. Leung, W. Allred

Objective:

To develop new and improved techniques for growth of GaAs and mixed III-V crystals in a coordinated program of growth and characterization.

Approach:

GaAs is being grown by a new Czochralski technique, by the travelling heater method, and by liquid encapsulated floating zone melting. The growth techniques and phenomena are themselves being studied. The crystals are characterized by X-ray topography, etching, Hall measurements, cathodoluminescence, etc.

Recent Progress:

GaAs crystals are being routinely grown by the new liquid-seal Czochralski technique. Mobilities are too low, so experiments are planned with different crucible materials. Up to two passes have been made in the liquid encapsulated floating zone melting of GaAs, but experimental difficulties are being encountered. A new casting technique has been developed for producing feed rods for the travelling heater method. Heat transfer in the gradient freeze and travelling heater methods has been treated theoretically. Experiments on organic analog have enabled evaluation of some of the parameters.

The maximum rate at which solid particles can be pushed by a growing crystal was found to increase with increased stirring. Particle mixtures were separated by using a gradually increasing freezing rate.

Hall measurements on bent GaAs samples provided evidence that dislocations may reduce mobilities. Slip bands were evident when bent samples were examined by cathodoluminescence in the electron microprobe.

References and Recent Publications:

1. R. J. Baughman, R. A. Lefever, W. R. Wilcox, "Evaporation of Sodium Chloride Melts", J. Crystal Growth 8, 317 (1971).
2. W. R. Wilcox, "Movement of Liquid Inclusions by Centrifugation", J. Crystal Growth 13/14, 787 (1972).
3. C. E. Chang and W. R. Wilcox, "Vitreous Boron Oxide: Drying and Moisture Absorption", Mat. Res. Bull. 6, 1297 (1971).
4. W. R. Wilcox and P. J. Shlichta, "A Survey of Movies on Crystal Growth", J. Crystal Growth, 15, 61 (1972).
5. K. Chen and W. R. Wilcox, "Boiling and Convection During Movement of Solvent Inclusions in Crystals", submitted to Ind. Eng. Chem. Fund.

1.1.4 Charge Storage in Silicon Nitride and Applications to
Computer Memories

F44620-71-C-0007, The Joint Services Electronics Program

W. R. Wilcox and W. L. Paterson

Objective:

To gain improved understanding of charge storage in silicon nitride films so as to be able to tailor-make computer memories utilizing silicon nitride films.

Approach:

Thermally stimulated currents will be measured in chemically-vapor deposited films doped with impurities.

Recent Progress:

Undoped films of silicon nitride in thicknesses ranging from 500A to 3000A have been grown on single crystal silicon substrates employing the reaction of silane and ammonia under a variety of preparative conditions. Capacitor structures employing a counterelectrode of aluminum or gold were fabricated for evaluation.

For the evaluation of the capacitor structures, apparatus was constructed for capacitance vs. voltage and thermally stimulated current measurements. The C/V apparatus employed phase sensitive detection, allowing small signal levels and ready decomposition of the equivalent circuit. The thermally stimulated current apparatus provides linear temperature ramps at rates 0.1 to 10.0 degrees from slightly below room temperature to 550 deg C. A high degree of conformity to the linear temperature vs. time relationship was obtained by feedback control of the rate rather than the temperature.

Computer studies of TSC spectra and their decomposition by a linear programming method were performed. Moderately separated peaks can be resolved, but broadened peaks and continua of levels have an ambiguous interpretation, with especial error occurring in determination of frequency factors.

Trapping levels deeper than 0.9 electron volt were found to be responsible for the semi-permanent (several year) charge storage effect which will be exploited for nonvolatile NDRO memory. These levels correspond to TSC peaks occurring at temperatures greater than 350 deg C, which is consistent with the demonstrated ability of these semiconductor memory cells to usefully retain data at temperatures in excess of 150 deg C.

1.1.5 Solution Growth of Bulk Crystals of Mixed III-V Compounds
for Electronics Device Applications

F44620-71-C-0007, The Joint Services Electronics Program
DAHC-15-71-G6, The Advanced Research Projects
Agency (DOD)

W. R. Wilcox and V. Yip

Objective:

- (a) To prepare bulk crystals of mixed III-V compounds.
- (b) To study physics of bulk solution growth by travelling-heater method.

Approach:

A solvent zone is passed through a solid rod by means of a moving heater. The crystals are examined for perfection. The interface position and shape is determined as a function of operating crystals. It has been discovered that GaAs crystals can easily be produced by the gradient-freeze technique.

Recent Progress:

Progress was made in understanding the physics of the travelling-heater method (THM) by heat transfer calculations and experimental determination of interface shapes and positions and temperature profiles. While exploring means to prepare cylindrical feed rods for the THM it was discovered that single crystals of GaAs can easily be prepared by the gradient freeze technique. These crystals have moderate dislocation contents and electrical properties, so are only suitable as substrate materials for epitaxial films and not directly for devices.

1. 1. 6 Epitaxial Growth of III-V Films from Oxygen Pumped
Solutions

F44620-71-C-0007, The Joint Services Electronics Program
DAHC-15-71-G6, The Advanced Research Projects
Agency (DOD)

J. M. Whelan

Objective:

To evaluate feasibility of reducing the growth temperatures of epitaxial films and increasing their impurities.

Approach:

The stability of oxides on the substrates requires very low oxygen activities for their removal by the growth solution. We propose to achieve the prerequisite activities at lower temperatures by oxygen pumping using solid electrolytes.

Recent Progress:

An apparatus was completed for growth of GaAs films from Ga solutions with low oxygen fugacities. A stabilized zirconia tube, a solid oxygen ion conducting electrolyte, was used as the solution container. Oxygen was pumped from the gallium solution electrolytically at rates approximately one hundred times faster than could be achieved by chemical removal with high purity hydrogen at 800°C. This established the first feasibility goal. This coincided with a recent downward estimate made elsewhere of the minimum equilibrium oxygen pressures which could be established with stabilized zirconia. This was judged to be sufficiently significant to warrant a redesign of the apparatus so that oxygen fugacities in gallium solutions can be measured which are two to three orders of magnitude below those of oxygen saturated solutions. It is anticipated that this approach may lead to reliable estimates of the oxygen content in GaAs samples. If so, this would be useful for resolving the adverse and beneficial effects of oxygen in GaAs devices which have been suggested over the past 15 years.

References and Recent Publications:

1. Dissertation: Joseph E. Greene, "Glow Discharge Spectroscopy for the Analysis of Thin Films", Ph.D., 1971.

1.1.7 Luminescence Due to Native Defects in CdS

F44620-71-C-0007, The Joint Services Electronics Program

M. Gershenzon and G. Turner

Objective:

To relate photoluminescent properties of CdS to native defect concentrations with a view toward development and optimization of small visible light emitters and lasers.

Approach:

Calculate defect concentrations for a series of CdS samples annealed under controlled conditions and quenched rapidly. Using the samples, low temperature photoluminescent and absorption spectra are measured and then related to the defect concentrations.

Recent Progress:

Samples have been rapidly quenched from both high and low temperature and photoluminescence remains bright but is different in character. Angle lapping experiments indicate quenching is fast enough. Reannealing indicates that samples can be cycled from one condition to another and returned reversibly. Photoluminescence shows many lines but absorption measurements are possible only on the lines of intermediate wavelength. Anneals corresponding to the end points of the series have been completed and should represent a 20:1 change in sulphur vacancy concentration.

1.1.8 Radiative Recombination in the Alloys $\text{Ga}_{1-x}\text{In}_x\text{P}$
and $\text{Ga}_{1-x}\text{Al}_x\text{P}$

F44620-71-C-0007, The Joint Services Electronics Program

M. Gershenzon and W. Hawk

Objective:

To determine the effects of alloy composition on the luminescence properties of the III-V alloys $\text{Ga}_{1-x}\text{In}_x\text{P}$ and $\text{Ga}_{1-x}\text{Al}_x\text{P}$.

Approach:

Alloy crystals are grown from a solution of excess metal and by liquid

phase epitaxy. Starting with the known luminescence spectra of GaP, shifts and weakening of these spectra with increasing alloy composition x ($x = 0$ is GaP) are used to determine changes in alloy optical properties.

Recent Progress:

The donor-acceptor pair lines in $\text{Ga}_{1-x}\text{In}_x\text{P}$ alloys, which could be resolved only for low In dopings in solution grown platelets and epitaxial layers at 4.2°K, have been observed for slightly higher In levels in experiments at 25°K where the nitrogen bound exciton becomes ionized and cannot produce light, resulting in an enhancement of the donor-acceptor luminescence. The epitaxial alloy crystals show resolved donor-acceptor spectral lines at In dopings where the energy shift due to In alloying is large enough to be detected, although the luminescence efficiency is weak. By performing accurate and time consuming experiments we will be able to measure the energy shifts of these weak donor-acceptor lines and to correlate them with the shifts in the sulfur bound exciton.

The doubly degenerate sulfur bound exciton in GaP is split into two levels in In doped crystals, with a splitting that increases as the amount of In in the alloy increases. This effect is attributed to a uniaxial strain associated with the incorporation of In into the GaP lattice and could be a function of crystal growth conditions.

Crystals of $\text{Ga}_{1-x}\text{Al}_x\text{P}$ have been grown from solution in vitreous carbon boats in order to avoid the Si contamination which occurs in growth inside quartz containers. The luminescence of these crystals shows only the broad far pair band of the GaP donor-acceptor pair spectrum, and the shift in this band indicates in excess of 10% Al in the alloy crystals. Growth of crystals with a lower Al content is made difficult by the large segregation coefficient favoring the incorporation of Al in $\text{Ga}_{1-x}\text{Al}_x\text{P}$.

1.1.9 Radiative Recombination in Silicon Due to Isoelectronic Traps and Deep Levels

F44620-71-C-0007, The Joint Services Electronics Program

M. Gershenzon and K. Kosai

Objective:

To search for new radiative recombination centers in silicon with the objective of developing efficient near-infrared light-emitting diodes.

Approach:

- (a) Investigate indium-doped float zone grown silicon which has been lithium diffused for photoluminescence and absorption due to lithium-indium close pairs acting as isoelectronic traps.
- (b) Study the luminescent properties of float zone grown silicon doped with impurities such as gold, copper, and zinc, known to produce numerous deep levels. Also, study the optical effect of diffused lithium on these deep levels, since lithium-impurity close pairs are expected to form which may act as isoelectronic traps.

Recent Progress:

A sample from an In-doped crystal was diffused with Li ($[Li] \sim 3 \times 10^{17} \text{ cm}^{-3}$, $[In] \sim 1 \times 10^{16} \text{ cm}^{-3}$) and examined using photoabsorption and photoluminescence with the sample immersed in liquid helium. In luminescence, radiation due to decay of excitons bound to both neutral In and Li was observed, while in absorption only a line due to creation of bound excitons at neutral Li could be identified. Observations showed that either the expected Li-In pair had not formed, or, if the Li and In had paired, the complex does not behave as a trap.

At sufficiently low temperatures ($T < 10 \text{ K}$) a series of sharp photoluminescence lines were observed on the low-energy side due to decay of excitons bound to neutral Li. We have studied similar lines in B- and P-doped Si. These lines do not appear at higher temperatures, whereas the associated bound-exciton emission can be observed to $T > 30 \text{ K}$. These lines have been previously observed in B-doped Si and it was suggested that they were related to the condensation of an electron-hole metallic-like liquid. We are trying to determine the exact mechanism responsible for the emission lines.

Wafers of Si were diffused with Au and Li. In those samples containing only Au, all of the intrinsic photoluminescence was quenched and no new radiation was observed. Silicon with both Li and Au impurities show an entirely new emission band having a sharp peak at 0.765 eV and an associated low-energy broad band. This emission was not observed in Si doped only with Li. We believe that Li-Au pairs are behaving as isoelectronic traps.

1.1.10 Studies of Semiconductor Surfaces

F44620-71-C-0007, The Joint Services Electronics Program

D. B. Wittry, K. Y. Chiu and P. A. Sullivan

Objective:

To obtain a better understanding of the phenomena that occur when electrons, photons or ions impinge on a solid surface in a gaseous environment.

Approach:

Measure surface potentials by electron mirror microscopy and by secondary electrons using a scanning electron probe; correlate surface potential changes with changes in surface recombination velocity; vary the nature of the surface states by changing the ambient gas or by implanting ions.

Recent Progress:

Constructed and tested an electron spectrometer for use with secondary electrons in the electron probe microanalyzer. A paper has been accepted for the 7th National Conference on Electron Probe Microanalysis describing this spectrometer.

The first scanning electron mirror microscope images were obtained and the theoretical calculations for the deflection bridge were verified.

References and Recent Publications:

1. "Techniques for Semiconductor Research with Electron Beam Instruments", Sixth International Conference on X-Ray Optics and Microanalysis, Osaka, Japan, Sept. 5-10, 1971.
2. "Studies of Semiconductors Using Optical Signals from Electron Microprobe Instruments", Symposium on Scanning Electron Microscopy, Japan Society of Applied Physics, Tokyo, Japan, Sept. 14, 1971.
3. "An Electron Spectrometer for Quantitative Measurements of Surface Voltages with Electron Microprobe Instruments", K. Y. Chiu and D. B. Wittry, accepted by the 7th National Conference on Electron Probe Microanalysis.
4. "Applications of Electron Microprobes to Solid State Electronics", D. B. Wittry, in Microprobe Analysis, ed. by C. A. Anderson, John Wiley & Sons, N.Y. (in press).

5. "Crystallographic Information from Scanning Electron Microscope Images", D. B. Wittry, Proc. Sixth International Conference on X-Ray Optics and Microanalysis (in press).

1.1.11 Electron Optical Characterization of Semiconductor
Materials

F44620-71-C-0007, The Joint Services Electronics Program

D. B. Wittry and R. E. Gauldin

Objective:

Provide service work for other JSEP research; perform research involving new techniques for characterizing semiconductors in the transmission electron microscope.

Approach:

Use the electron probe microanalyzer for x-ray microanalysis; use selected area electron spectrometry in the transmission electron microscope to obtain information about composition and chemical bonding in the TEM specimens.

Recent Progress:

Installed and reconditioned the Hitachi HU10 instrument, constructed adapters for the magnetic prism spectrometer, made preliminary tests of the spectrometer and developed techniques for making thin semiconductor specimens. A system for feedback regulation of the high voltage supply of the microscope has been designed and is now under construction.

References and Recent Publications:

1. "Modification of the High Voltage Supply of an Electron Microscope for Improved Stability", R. E. Gauldin and D. B. Wittry, paper submitted to the 13th Annual Meeting of the Electron Probe Analysis Society of America.

1. 1. 12 Cathodoluminescence of GaAs and Its Alloys

DAHC-15-71-G6, Advanced Research Projects Agency (DOD)

D. B. Wittry, W. Lin, H. C. Marciniak

Objective:

To study mechanisms for spontaneous radiative recombination and conditions for stimulated emission of electron beam excited GaAs and $\text{GaAs}_x\text{P}_{1-x}$.

Approach:

Observe cathodoluminescence spectra of various temperatures and electron beam current densities on GaAs and GaAs-GaP alloys near the direct-indirect crossover point; introduce asymmetry by strain and by magnetic fields; try to correlate results with theoretical models for recombination processes.

Recent Progress:

Cathodoluminescence spectra have been obtained from several n type specimens of GaAs and GaAs-GaP alloys as a function of current density in the electron beam. No evidence for super-radiance has been seen at room temperature. Attempts have been made to reduce surface recombination by a surface alloying technique, however, these have also not been unsuccessful as yet. Additional experiments are in progress on specimens subjected to uniaxial compression.

The results at temperatures down to 30°K on GaAs-GaP alloys are encouraging and further experiments as well as theoretical interpretation of the results is in progress.

1. 1. 13 Investigations of Dislocations in GaAs

DAHC-15-71-G6, Advanced Research Projects Agency (DOD)

J. Esquivel, D. B. Wittry and W. Lin

Objective:

To study the effect of dislocations on recombination processes in GaAs after plastic bending at elevated temperatures.

Approach:

Use scanning electron microscopy with detection of infra-red cathodoluminescence to observe dislocation densities and configurations; compare with x-ray topographs; study both p and n type material with various orientations of the bend axis to correlate with electronic properties of the dislocations.

Recent Progress:

Cathodoluminescence images from n type GaAs ($10^{17}/\text{cm}^3$ Te) and undoped ($10^{16}/\text{cm}^3$) GaAs have indicated that it will be possible to obtain dislocation densities up to about $10^7/\text{cm}^2$ with an accuracy of $\pm 10\%$. Also, it appears to be possible to correlate the dislocation arrays with the known slip planes in GaAs. Further studies are in progress using different directions for the bend axis and using p as well as n type GaAs. It is anticipated that this technique will be an effective non-destructive method of studying deformed semiconductor materials.

1. 1. 14 Avalanche Multiplication in Semiconductors

F44620-71-C-0007, The Joint Services Electronics Program

C. R. Crowell, C. L. Anderson and Y. Okyto

Objective:

To measure ionization coefficients of electrons and holes in Si, GaAs and GaP both at low electric fields and in a predicted high field asymptotic region which may be useful for stable high gain devices.

Approach:

Study of multiplication by photoinjected carriers in Schottky barrier configurations--a new approach which should permit a unique separation of the effects of multiplication of holes and electrons (very important for device (IMPATT) characterization at high frequencies and for noise considerations). Theoretical refinement of the way in which ionization coefficients are defined is also needed.

Recent Progress:

Experimental:

The development of well-defined Schottky barrier avalanche structures is nearly complete. Schottky barrier guard rings in an oxide passivated planar structure on 10μ thick, $25\Omega\text{ cm}$ epitaxial layers are being used. These structures are intended to permit a clear distinction between

electron and hole initiated ionization processes. This distinction is important for understanding the noise and optimum operation of IMPATT and photo-avalanche diodes.

Theoretical:

a. Photoinjection. The above experimental measurements require a clear understanding of the electric field dependence of photoinjection in Schottky barriers. A theoretical calculation of quantum mechanical tunneling effects for this case has been completed for a barrier model which for the first time correctly includes effects of conservation of transverse momentum and Thomas-Fermi screening in the metal.

b. Coupled Electron Hole Ionization Rates. Theoretical work revealed that the conventionally accepted definitions for electron and hole ionization coefficients implicitly convolve effects of electrons and holes which depress the coefficients considerably (i.e., according to current usage). A modified interpretation allows removing the requirement of anomalous threshold energies (too large by a factor of 4) which has been needed to explain recent experimental results in the case of Si.

References and Recent Publications:

1. "Threshold Energies for Electron-Hole Pair Production by Impact Ionization in Semiconductors", C. L. Andersen and C. R. Crowell, Physical Review, B. 5, pp. 2267-2272 (1972).
2. "Energy Conservation Considerations in the Characterization of Impact Ionization in Semiconductors", Y. Okuto and C. R. Crowell, submitted to Physical Review.

1.1.15 Experimental Analysis of Impurity Energy Levels in Semiconductors

DA-ARO-D-31-124-71-634, U.S. Army Research Office,
Durham

C. R. Crowell, C. L. Anderson, M. Beguwala and
K. Nakano

Objective:

To demonstrate how impurity energy levels in semiconductors can be characterized by capacitance studies using Schottky barrier (metal-semiconductor) contacts. Achieving this aim also clarifies the effect of

impurities on the capacitance of semiconductor devices and hence on their charge control capabilities.

Approach:

The project encompasses both theoretical and experimental work. From measurements of the frequency and bias dependence of Schottky barrier capacitance and conductance, impurity levels, the capture cross-sections for majority carriers, and the concentration of the impurity species will be determined.

Recent Progress:

a. Theoretical: Crowell and Nakano's theoretical work on the frequency dependence of Schottky barrier capacitance is in press. Beguwala and Crowell are developing a more comprehensive solution in differential equation form which enables one to evaluate the complex capacitance (i. e., conductance and susceptance) of a Schottky barrier in the presence of several deep lying impurities. Our approach also facilitates the modeling of the impedance with lumped circuit elements. We have established that our previously reported three element model is not particularly satisfactory for a distribution of deep levels and even for a single deep level does not bear a simple relationship to the impurity time constant and concentration. Our present approach yields an equivalent circuit with $3r+1$ frequency independent elements for a system with r impurity levels. The $R_n C_{dn}$ product equals the time constant of the n th level over the frequency range of interest. The capacitances have simple relationships to the concentrations and energy levels of the different impurity species. This model can be uniquely synthesized from experimental C vs ω measurements at a single temperature if one can measure capacitance far enough into forward bias. Failing this one need to consider C vs temperature and C vs V measurements along with C vs ω measurements for a unique synthesis. A paper on this work is being written for publication.

b. Experimental: Roberts and Crowell have submitted for publication their experimental work titled "Capacitance Effects of Gold and Copper Impurity Levels in Pt-N Type Si Schottky Diodes". Procedures for preparing good Schottky and ohmic contacts to both p and n-type silicon are being refined. The electronically balanced broad-band capacitance and conductance measurement system is being revised. Pilot measurements indicated a need for a slower bias sweep to enable use of the longer time constant of the phase sensitive amplifier for a higher signal to noise ratio. This modification is under construction. The preamplifier has been redesigned and is being rebuilt to operate near critical damping. This will allow the system to measure capacitance transients which occur within a time span of a few seconds. The system can now display directly recorded data in the form of $\frac{1}{C^2}$, $\frac{1}{C^3}$ and $\ln C$ vs V . Facilities for

programming C- ω measurements are under construction.

Recent Publications:

1. C. R. Crowell and K. Nakano, "Deep Level Impurity Effects on the Frequency Dependence of Schottky Barrier Capacitance", Solid State Electronics, in press.
2. G. I. Roberts and C. R. Crowell, "Capacitance Effects of Au and Cu Impurity Levels in Pt-n Type Si Schottky Barriers", submitted to Solid-St. Electronics.

1.1.16 GaAs Growth and Characterization

DAHC 15-71-G-6, U.S. Army (ARPA)

C. R. Crowell, C. L. Anderson, S. Joshi, C. Huang

Objective:

- Task "a": Tunnel and Thermal Effects in Photoemission from Schottky Barriers: To determine the corrections to a photothreshold plot which is customarily used as primary indication of Schottky barrier height.
- Task "b": Schottky Barrier Capacitance Characterization of Impurities: To determine the extent to which capacitive characterization of Deep Level Impurities is possible in GaAs.
- Task "c": High Impedance Hall System: To construct a high impedance temperature controlled Hall system for impurity characterization in GaAs.

Approach:

- Task "a": Theoretical calculations of quantum mechanical transmission coefficients of electrons incident in a Schottky barrier are convolved. The photoexcited spectrum of electrons are observed to predict field dependence of the photocurrent.
- Task "b": Theoretical guidelines provided by work under DA-ARO-D-31-124-71-G34 are being used to analyze experimental measurements.
- Task "c": A balanced varactor bridge amplifier with guarded feedback to suppress leakage and common mode effects is being made for use in conjunction with a liquid helium Hall effect cryostat.

Recent Progress:

- Task "a": The paper accepted for publication covers only thermal effects in photoemission, but is useful because the normalized approach is useful no matter what the metal-semiconductor combination. Our extension of the approach with the tunneling effects is now near completion and will be useful in interpreting results on GaAs where tunneling effects appear to predominate over thermal effects at 300°K.
- Task "b": Point-by-point C-V measurements were made on Pt-n type GaAs Schottky barriers with frequency dependent results observed, particularly near zero bias and in forward bias. Further detailed data is required before circuitry is completed for C-V and C-W scanning.
- Task "c": The Hall system circuitry is now operational and has demonstrated a capability of measuring samples with impedances of the order of $10^{10}\Omega$ with good accuracy. Effective leakage impedances of the voltage measuring circuitry and the current source are $\approx 10^{12}$ ohms. A low impedance mode of operation with \approx microvolt sensitivity and digital readout is also available within the same system.

References and Recent Publications:

1. "A Convenient Operational Equivalent to the Fowler Photothreshold Plot," by Crowell, Kao, Anderson and Rideout, Surface Science, accepted for publication.

1.1.17 Experimental Studies of Defect-Induced Vibrational Mode Absorption

F44620-71-C-0067, The Joint Services Electronics Program
GK-25144, National Science Foundation

W. G. Spitzer

Objective:

To accomplish identification and characterization of a variety of point defects in semiconductors. In most cases these defects involve impurities introduced as dopants in the semiconductors. Once identified, the changes in defect concentration as a result of changes in environment can be observed directly.

Approach:

The identification is accomplished by measuring the high frequency localized vibrational modes associated with the impurity. At present, the modes are observed by infrared absorption although it is intended to extend the measurements to include Raman scattering.

Recent Progress:

a) GaAs: Mg

The interest in Mg, which is an acceptor in GaAs, results from some ambiguities in the interpretation of the infrared absorption of Li-compensated material doped with Mn, Cd, or Zn. The models proposed for the Li-acceptor ion pair were questioned by some later E. P. R. results. The infrared absorption of Mg-doped GaAs compensated by Li diffusion is measured and the results are compared with those for similar material compensated by electron irradiation and for double-doped material. The absorption bands observed in the GaAs: Mg-Li are consistent with a model of the following type:

- A) There is only one type of (Mg-Li) pair
- B) Each pair has only one Li paired with each Mg
- C) The Li is in an interstitial position
- D) The (Mg-Li) pair has orthorhombic or lower symmetry
- E) The pair axis is probably in a $\langle 100 \rangle$ direction

b) GaAs Ion Implanted with Si

The infrared absorption of localized modes for ion implanted Si in GaAs have been observed. The implants were at room temperature, at energies of 1.0 and 1.5 MeV, and fluences $\sim 10^{17}$ ions cm^{-2} . Bands previously attributed to Si_{Ga} and Si_{As} defects were observed and the effect of isochronal annealing studied. A $(\text{Si}_{\text{Ga}}-\text{Si}_{\text{As}})$ pair band was observed after annealing. For most annealing conditions the bands were found to either grow or show little change with increasing anneal temperature. However, between 500 and 650°C substantial reverse annealing was observed for both Si_{Ga} and Si_{As} . This reverse annealing cannot be the result of pair formation and is being investigated further. The electrical data for these high fluences and energies, show no apparent correlation with the Si defect concentrations deduced from the optical data. The conductivity, even after 900°C annealing, is probably controlled by residual damage left in the implanted layer.

References and Recent Publications:

1. Dissertation, Pat C. Leung, "Infrared Absorption by Free Carriers in P-Type Silicon", Ph.D., 1971.
2. Dissertation: Lyn H. Skolnik, "Application of Infrared Active Localized Vibrational Modes to the Investigation of Impurity Incorporation in Semiconductors", Ph.D., 1972.

3. Dissertation: Albert E. Cosand, "Infrared Absorption Studies of Localized Vibrational Modes and Lattice Modes in Ge_xSi Ph.D., 1972.
4. "Investigation of Te-Doped GaAs Annealing Effects by Optical and Channeling-Effect Measurements", J.A.P. 42, 3982 (1971), with I. V. Mitchell, J. W. Mayer, J. K. Kung and W. G. Spitzer.
5. "An Infrared Localized Vibrational Mode Technique for Measuring Segregation Coefficients", J. Phys. Chem. Solids 32, 1 (1971), with L. H. Skolnik, W. P. Allred and W. G. Spitzer.
6. "Infrared Absorption of Lattice Modes and the Silicon Local Mode in $\text{Ge}_x\text{Si}_{1-x}$ Alloys", J.A.P. 42, 5230 (1971), with A. E. Cosand and W. G. Spitzer.
7. "Infrared Localized-Vibrational-Mode Absorption of Ion-Implanted Aluminum and Phosphorus in Gallium Arsenide", J.A.P. 42, 5223 (1971), with L. H. Skolnik, W. G. Spitzer, A. Kahan, and R. G. Hunsperger.
8. "Localized Vibrational Modes in Semiconductors: Infrared Absorption", Festkörperprobleme XI, Vieweg (Pergamon), 1971, pp. 1-44, W. G. Spitzer.

1.2 QUANTUM ELECTRONICS

1.2.1 Frequency Coupling in High Gain Optical Amplifiers

F44620-71-C-0007, The Joint Services Electronics Program

J. H. Parks

Objective:

(1) To develop experimental and theoretical techniques for studying nonlinear wave propagation in high gain amplifiers, and (2) to relate the measured nonlinear parameters to applications in laser communication technology.

Approach:

To measure the nonlinear coupling between two optical fields travelling through a dye laser amplifier at frequencies ω_1 and ω_2 . When these frequencies both lie within the dye radiative linewidth, the subsequent coupling depends strongly on the difference $(\omega_2 - \omega_1)$. A tunable dye laser will provide the variable frequency fields. The related theoretical calculations will proceed from a perturbative treatment of the atomic interaction with two travelling wave fields having wave vectors \vec{h}_1 and \vec{h}_2 .

Recent Progress:

The saturation behavior of two optical fields in an absorbing or amplifying medium is being investigated. An intense, saturating dye laser pulse near 4400 \AA and a weak probe field at 4400 \AA from a c.w. He-Cd laser are employed in this experiment. The modulation of the c.w. laser absorption in Perylene (liquid phase) as a function of the dye laser wavelength allows a direct measurement of the nonlinear coupling properties of the absorbing transition. The high power dye laser has been constructed with an optical pumping source supplied by a frequency doubled ruby laser. This will provide dye laser pulses of ~ 1 megawatt peak power and ~ 20 nanosec widths, tunable near 4400 \AA . A theoretical model describing the nonlinear coupling between two monochromatic fields having wave vectors \vec{k}_1 and \vec{k}_2 has been developed. For the case of a Doppler broadened medium, the nonlinear response suggests unique interactions between the two fields even when the fields travel a relatively large angles for which $|\vec{h}_1 - \vec{h}_2| \approx \Delta\omega_D$ where $\Delta\omega_D$ is the Doppler linewidth. This particular model has not been considered previously and leads to interesting results which have applications for large aperture high power gas lasers such as CO_2 .

References and Recent Publications:

1. "Optical Broadband Amplifier", J. H. Parks, A. Javan, J. Opt. Soc. Am. 61, 658 (1971).
2. "Theory of Noise Amplifiers", J. H. Parks, F. Hopf, J. Opt. Soc. Am. 61, 659 (1971).
3. "Broadband Amplifiers", J. H. Parks, Esfahan Symposium on Fundamental and Applied Physics, Esfahan, Iran (proceedings to be published).

1.2.2 Experiments with Laser Optical Sources

GH 32401, National Science Foundation

W. L. Faust

Objective:

To conduct theoretical and/or experimental studies in three areas:

1. High Intensity Resonance. In the course of previous work involving high intensity illumination of GaP material with visible laser frequencies, quenching of visible fluorescence by the infrared beam was observed. The current objective is to substantiate the assignment of this effect to photoionization of the bound-exciton states responsible for the fluorescence and to determine the minimum energy necessary for such photoionization.
2. Excitation Spectra. In the course of the previous work described above it was also discovered that fluorescent spectra are highly dependent upon the visible frequency employed for excitation. Current efforts are now being directed to further study these effects and to exploit them for assignment of specific spectral features in the fluorescence to specific impurities.
3. Raman Scattering. The objective is to construct a detailed theory of the relation between Raman scattering and visible-infrared mixing.

Recent Progress:

1. High Intensity Resonance Studies. Fluorescence-quenching has been found to occur only if the infrared pulse is properly coincident in time with the exciting pulse of visible light. This would seem to eliminate simple heating as the mechanism and to indicate a mechanism which will be more interesting to study. Further, it was demonstrated that fluorescence from impurities previously reported as deeply bound is not readily quenched, whereas certain shallow systems are more readily quenched. A further objective is to illuminate the material with monochromatic radiation to determine a minimum energy for quenching. This should be the binding energy.

2. Excitation Spectra Study. We have discovered a prominent case of enhancement of fluorescence from a particular impurity in the presence of others through resonant excitation. The effect suggests that this is an imperative direction for future exploitation of tunable visible dye lasers.

3. Raman Scattering. This work is at an advanced stage in development of the theory of light scattering from thermal and zero-point infrared frequency fluctuations in a crystalline lattice. The models predict with some success the intensity versus frequency--including resonance peaks, widths, asymmetry, and shifts for varying parameters--both for LO excitations and for TO excitations. The LO calculation accommodates the contribution of a plasma of charge carriers to the linear dielectric response; but, it does not account for scattering from carriers. This seems to be adequate for the heavily-damped plasma of GaP. The crystal is modeled by Lorentz resonance parameters (determined from linear infrared experiments) and by the nonlinear parameters of Faust and Henry (measured in an experiment in which coherent visible and infrared beams are mixed).

1.2.3 Laser Induced Damage in Thin Films and Substrate Surfaces

19628-71-C-0220, Air Force Cambridge Research Laboratories

N. Alyassini, T. Colbert, J. H. Parks

Objective:

Structural damage in thin films and at substrate surfaces limits high power laser operation and the reliability of antireflection coated optical components. This investigation is directed toward an understanding of the physical processes leading to material breakdown.

Approach:

The development of techniques to measure continuous time evolution of damage is a primary approach in these studies. A continuous He-Ne laser is reflected from the local region which is undergoing damage induced by a high power ruby laser pulse. Studies of the time variation in the reflected probe intensity yield the temporal characteristics of the damage processes.

Recent Progress:

The time evolution of damage to thin films and substrate surfaces was observed by monitoring the intensity variation of a He-Ne beam reflected from the film or surface during irradiation by a Q-switched ruby laser. Monolayered films including ZnS, CaF₂ and NaCl on fused silica substrates were studied, as well as uncoated fused silica and LiF substrates. When the probe beam is reflected from the exit surface of a substrate sample, the reflected intensity was observed to decrease within the timescale range of 20-200 nanoseconds to a final value significantly less than that prior to damage. When the probe is spatially offset from the damage region, the reflected intensity decreases and then returns to approximately the pre-damage value within 0.2-0.3 μ sec. This reversible effect was observed to be associated with a propagating disturbance on the substrate surface moving with approximately the speed characteristic of a Rayleigh surface wave. The risetime and duration of the plasma which accompanies surface damage was also measured.

The reflected intensity from thin films was observed to increase or decrease depending on the film index of refraction. The monolayer film samples exhibited reflectance changes on the timescale of the ruby pulse, however, an offset probe position indicates this change can occur after a time delay of $\sim 0.1 - 0.2 \mu$ sec.

1.2.4 Time Resolved Spectroscopy with Pulsed Lasers

A. Scalabrin, J. H. Parks, R. Brown, L. Singer

Objective:

Molecular relaxation processes can be measured in detail by observing the time resolved emission spectrum from excited electron states. This method is particularly applicable to large organic molecules in which many competing decay channels can be separated by combined measurements of time and wavelength dependence.

Approach:

Intense nanosecond laser pulses will be used to produce a high density of molecules in a specific excited electronic state within the timescale of the relaxation process under consideration. This provides an opportunity to study the spectrum of weakly emitting species and resolve the ensuing decay time within the laser pulsewidth.

Recent Progress:

A. Prompt and Delayed Fluorescence from Benzophenone

This research has provided the first complete time resolved spectral distribution of the prompt fluorescence and in addition new data supporting previously described E-type delayed fluorescence from benzophenone. The filtered output from a 50 kW pulsing nitrogen laser was passed into 1 cm square or 6 mm cylindrical Pyrex cells containing benzophenone samples.

The emission was monitored at right angles to the excitation through a cutoff filter (2 M aqueous potassium nitrite, 2 cm path length) to remove scattered laser light, and then through a one-half meter Bausch and Lomb monochromator onto an RCA IP21 photomultiplier tube. The signal was stored and averaged in a Princeton Applied Research Model 160 Boxcar Integrator and (or directly) displayed on a Hewlett-Packard 183 oscilloscope (250 MHz).

The spectral distribution of the fast decay from benzophenone in benzene solution at room temperature was obtained with the PAR boxcar integrator as follows. The signal from the photomultiplier was repetitively fed into the PAR instrument (laser rep. rate, 10-30) where it was stored and averaged. A segment of the total signal, at various times after triggering of the boxcar, was selected and stored by adjusting the time delay T_d and sampling gate, T_g , of the boxcar. The spectral distribution of this segmented signal was determined by the choice of T_d and T_g in conjunction with a display of the output from the boxcar on a strip

chart recorder as the monochromator wavelengths were scanned by means of a motor drive.

The PAR boxcar integrator used in our experiment can be used with T_g as short as 10 nsec or as long as 0.5 sec while the T_d can be made very close to 0 sec. Thus, nsec decays can be sampled and time resolved from longer decays. By comparison, mechanical devices, such as the phosphoroscope, can be employed only for sampling relatively long-lived (\geq msec) emissions.

A series of spectra at room temperature at different delay times reveals the delayed fluorescence component in the emission from benzophenone. At $T_d = 0$, the observed spectrum is a composite of the fluorescence and phosphorescence. At $T_d > 10$ nsec, the prompt fluorescence has ended and the spectrum might be expected to reveal only the phosphorescence spectral distribution. However, residual intensity is observed as a shoulder at 3800 Å. This intensity decays at the same rate as the phosphorescence as indicated by a constant ratio for (intensity at 3800 Å)/(intensity at 5250 Å). This result is consistent with an E-type delayed fluorescence mechanism as the source of the residual high energy emission.

In summary, we conclude that the emission from benzophenone at room temperature consists of prompt fluorescence, delayed fluorescence, and phosphorescence based on our observations of (a) a very short-lived emission from benzophenone (< 6 nsec) at 300°K and 77°K. (a) a longer-lived emission (μ sec) at 300°K which is a composite of the phosphorescence emission and an emission having a spectral distribution characteristic of the prompt emission. (c) a long-lived (msec) emission at 77°K which shows only the phosphorescence.

B. Vibrational Relaxation in the Excited States of Large Molecules

The large number of vibrational modes in multi-atomic molecules does not allow a vibrational level to be easily resolved for the purpose of measuring vibrational relaxation processes. The use of short (5 nanosec), intense pulses provided by a tunable dye laser offers a unique method of measuring these relaxation phenomena. As the laser wavelength is tuned to excite a molecule into different higher electronic-vibrational levels, the spectral distribution of the ensuing emission becomes very sensitive to the gas pressure. In particular, the emitted intensity versus wavelength distribution will be independent of pumping wavelength and gas pressure only when the excited state molecules have relaxed into the lowest vibrational level. At lower pressures (.01 - 1 mm Hg), the emission will occur before collisional relaxation and then exhibit a spectral distribution characterizing the higher levels.

Research underway includes the measurement of vibrational relaxation within the first excited state of biacetyl using this technique. These studies will be extended to molecules of similar structure, glyoxyl and benzil.

1.2.5 Study of Laser-Irradiated Thin Films

F19628-71-C-0220, Air Force Cambridge Research
Laboratories

L. G. DeShazer, E. A. Maunders, B. E. Newnam
and H. R. Owen

Objective:

The damage resistance of state-of-the-art dielectric thin-film reflectors and antireflection coatings to laser radiation is being studied. Particular attention is given to the measurement of a threshold for laser damage to thin films.

Approach:

A TEM₀₀ Q-switched ruby laser is used to damage mono-, bi- and multi-layered coatings of the materials TiO₂, SiO₂, ZrO₂, MgF₂ and ZnS on substrates of glass, rocksalt and spinel. Damage threshold energy and power densities are measured with attention paid to dependences on laser beam spot-size, film material and thickness, substrate condition and incipient scattering of the film.

Recent Progress:

The damage experiments were continued during the reporting period in studying the variation of the damage threshold energy and power densities with adjustments in the film, substrate and laser parameters. Emphasis was placed on the establishment of a sensitive and reliable criterion for the onset of damage. Many investigators of laser-induced damage to surfaces of transparent dielectrics have observed a luminous surface spark whenever physical damage occurred. Some researchers have proposed that the spark is responsible for the observed damage, and it has thus become a convenient practice to identify the spark threshold as the damage threshold. We have used three methods to monitor the onset of damage: a) spark detection using a sensitive photomultiplier with a narrow band interference filter, b) laser-induced increase in the scattering of a He-Ne laser probe, and c) optical microscopic observation of film breakup.

The interesting result is, that for monolayer films, an increase in He-Ne light scatter was observed prior to or at the spark threshold, depending on the film material. If the initial He-Ne scatter levels were low enough, we would expect the same result for multilayer films also. It was shown that laser-induced scatter occurs before spark initiation for films with high indices of refraction.

Another recent aspect of this study has been the investigation of a correlation between scattering (before damage) from thin-film coatings and their damage thresholds. The scattering was measured by the intensity of light scattering at about 135° from the direction of the incident beam. Since there is a strong wavelength dependence for the diffuse reflectance from a dielectric film, we used a severely attenuated output from the single-mode Q-switched ruby laser as the measuring beam.

References and Recent Publications:

1. B. E. Newnam and L. G. DeShazer, "Spot-Size Dependence of Laser-Irradiated Damage Threshold of Dielectric Thin Films," IEEE JQE 8, 611 (1972).
2. L. G. DeShazer and B. E. Newnam, International Conference on Thin Films, Venice, Italy, May 15-19, 1972.
3. L. G. DeShazer and B. E. Newnam, "Study of Laser-Irradiated Thin Films," 1972 ASTM-NBS Laser Damage Symposium, Boulder, Colorado, June 14-15, 1972.

1.2.6 Transient Behavior of Transverse Modes in High-Power Pulsed Lasers

AFOSR-71-2066, Air Force Office of Scientific Research

L. G. DeShazer, B. E. Newnam and G. L. McAllister*

Objective:

We are investigating theoretically and experimentally the transient behavior of transverse modes in high-power Q-switched laser oscillators. This research will cover an important deficiency in the present characterization of "single-mode" pulsed lasers emitting high powers, a characterization that is urgently needed in order to achieve the total capability of giant-pulse lasers in optical systems.

Approach:

During this program, a computer analysis will derive for high-power Q-switched lasers the transverse patterns, which will be compared to experimental patterns of a giant-pulse ruby laser. Emphasis will be

* Northrop Corporate Laboratories, Hawthorne, California.

placed on understanding the single mode performance when various method of Q-switching (passively or electro-optically) are used to pulse the laser.

Recent Progress:

The computer program used prior to this grant was rewritten and upgraded during this report period. The number of radial increments was increased from eleven to forty-one, while the number of temporal increments per round trip was kept the same as before. This improvement enabled us to calculate the transverse patterns for cavity Fresnel numbers up to ten with single pass gains of twenty. The computer program calculates power density and relative phase as a function of radial position and time in the aperture plane, the total power (spatially integrated) versus time, and the radial distribution of the energy density in the aperture plane. Further, these quantities can be calculated at any distance from the aperture.

At present, we have observed that the pulsewidths are the same up to Fresnel Number of 5. At Fresnel Number 8 the gain saturation perturbs the profile greatly, producing spikes in the temporal profile. Such temporal spikes have been experimentally observed with this calculated behavior, but this is the first calculation of this observation.

Several attempts were made during the computer analysis to include the effect of a saturable absorber on the transverse mode distortion, but several inconsistencies in the calculations resulted. These inconsistencies were traced to the method used for the interaction of the forward and backward traveling portions of the light pulse with the absorber. Now we are exploring several suggestions as to a method of including the saturable absorber in the computer analysis.

References and Recent Publications:

1. B. E. Newnam and L. G. DeShazer, "Criterion for Obtaining Single-mode TEM₀₀ Operation of High-Powered Pulsed Lasers," to be presented at the Meeting of the Optical Society of America, San Francisco.

1.2.7 Advanced Nonlinear Absorption Devices for Laser Systems

NGL-05-018-044, National Aeronautics and Space Administration

L. G. DeShazer and J. W. Austin

Objective:

We are investigating theoretically and experimentally the behavior of optical resonators containing saturable absorbers. Even though saturable absorbers have been used in laser systems as passive switches and modulators since 1964, the operation of these absorbers in conjunction with optical resonators has not been adequately described as yet. Recently, a comprehensive theoretical treatment of their behavior was developed and now this general theoretical approach will enable us to design a second generation of saturable-absorber optical devices.

Approach:

The features of this problem are succinctly contained in the problem of a Fabry-Perot resonator containing a saturable absorber. Such a device is called a saturable resonator. A general steady-state solution to the performance of the saturable resonator has been obtained and was published in the dissertation of J. W. Austin. Now, this solution has given suggestions as to a method of including the saturable absorber in a computer analysis of the transient solution.

Recent Progress:

Presently, we are investigating the time-dependent analysis of a saturable resonator. An analytical solution of the rate solutions is tractable only for a step- or square-pulse input; hence, for more complicated pulse shapes, such as a Gaussian shape, we resort to numerical techniques. We have begun an analysis of the saturable resonator for pulses having widths much larger than the response time of the absorber. Transfer curves describing the transmission of a laser pulse have been obtained for this case. For a given peak intensity and a specific absorber system the intensity level at which the saturable resonator turns "on" can be adjusted by varying mirror reflectivity and/or low level absorber transmission.

By these adjustments significant narrowing of a pulse can be achieved. Also it was demonstrated that the transmitted pulse shows an asymmetry about the peak; this asymmetry is due to the hysteresis of the saturable resonator when it operates in the bistable region. Experiments are being

conducted to verify these theoretical predictions.

In addition to these pulse studies, an analytic solution is being attempted for the case of a Fabry-Perot resonator with an absorber whose transmission decreases with increasing intensity. This solution may be of interest for studying laser damage to thin films.

1.2.8 Laser and Spectral Properties of Rare Earth Crystals

AF-AFOSR-69-1622A, Joint Services Electronics Program

Gift, Union Carbide Corporation

L. G. DeShazer, J. K. Guha and L. M. Hobrock

Objective:

We are developing methods to allow comprehensive application of the theories of relaxation processes in rare-earth-ion/solid systems to quantum electronic devices of current interest. It is well known that certain rare-earth crystals, such as Nd/YAG, have achieved relatively high performance as solid state lasers. However, development of rare-earth lasers during the past ten years has proceeded primarily on an empirical basis. Now, we recognize that the theories of RE^{3+} /solid systems are sufficiently precise to provide quantitative guidance in selecting new, potentially useful RE^{3+} /solids for use in laser devices.

Approach:

We will develop computer software to permit efficient computation of radiative transition matrices for all $4f^n$ systems. Concurrently we will experimentally determine multiphonon parameters for important host materials by performing lifetime measurements on selected RE^{3+} /solid systems, and determine the intensity parameters by measuring intensities of these selected systems.

Recent Progress:

There has been a recent shift of interest from YAG to yttrium orthoaluminate (YAP) as a host for neodymium. The important difference between the two materials is that while YAG is cubic and optically isotropic, YAP is orthorhombic and optically biaxial. The anisotropic nature of YAP makes it of interest because the wavelength, polarization, and output energy is a function of crystallographic orientation. This feature has been emphasized strongly because it allows certain laser characteristics to be optimized through the proper choice of rod orientation. We have studied the polarization properties of the Nd:YAP spectra

as a function of crystal direction. The polarization of each transition has a different elliptical nature, but the anisotropic optical properties of YAP have confused the analysis of the polarization measurements since the birefringence of YAP modifies the polarization states of the spectral lines. Our polarization analysis will be completed soon.

An extensive study of the Nd:YAP laser was made. The input energy versus output energy was measured for the two strongest transitions (1.0645 and 1.0795 μ) for various crystal directions. The experiment involved a plane mirror resonator with a long pump pulse (600 μ sec). The slope efficiency was found to be highest for the a-axis rod with chromium, 3.3 times that of YAG. The a-axis rod at 1.08 μ with chromium seems to be the best choice as a laser material for pulsed laser action. The same is not true for CW operation; our preliminary studies indicate that the b-axis rod with chromium seems to be the most suitable.

References and Recent Publications:

1. L. M. Hobrock, L. G. DeShazer, W. F. Krupke, G. A. Keig and D. E. Witter, "Four-Level Operation of Tm:Cr:YAlO₃ at 2.35 μ ," IEEE JQE 8, 533 (1972).
2. J. K. Guha, L. G. DeShazer, G. A. Keig and D. E. Witter, "Polarization and Crystal Direction Effects on Laser Performance of Neodymium/Yttrium Orthoaluminate," IEEE JQE 8, 536 (1972).

1.2.9 Theory of Electromagnetic Scattering Processes at Resonance, and With Intense Fields

F44620-71-C-0007, The Joint Services Electronics Program

R. W. Hellwarth and J. H. Marburger

Objective:

To be able to interpret and predict the spectrum of the electromagnetic radiation that is scattered by matter from an incident, monochromatic, electromagnetic wave as its frequency is tuned through a resonance of the scattering medium and to understand the modifications of the spectrum when the incident field strength is very large.

Approach:

Our approach will be theoretical but directed toward meeting the needs of the experimenters who will soon be studying the details of resonance scattering for the first time with new tunable laser sources. (Some of these sources are also capable of producing very high optical intensities.)

Recent Progress:

This is a new task. The work has only recently become of interest as practical and reliable coherent infrared and optical sources have approached development.

1.2.10 Investigating Mode Competition Effects in High Power Gas Lasers

DA HOI-71-C-1476, U.S. Army

W. H. Louisell

Objective:

To study resonators with diverging central portion and converging rims to spread out mode volume and simultaneously reduce diffraction loss for single mode, high power operation.

Approach:

The integral equations describing wave propagation in unstable rimmed mirrors were solved by computer. Design parameters were found for a fundamental mode with large mode volume, low diffraction loss and discrimination against higher order modes.

Recent Progress:

Theoretical work has terminated and a paper has been written for publication (see below).

References and Recent Publications:

1. "Transverse Mode Suppression Using Rimmed Unstable Resonators", M. Lax, C. E. Greninger, W. H. Louisell and W. B. McKnight, to be published.

1.2.11 Studies of Coherent Optical Devices

F44620-71-C-0007, The Joint Services Electronics Program

W. H. Steier

Objective:

The invention, evaluation, and application of devices for the control and detection of coherent electromagnetic radiation in the infra-red and optical spectrum.

Approach:

- a) Study methods to stabilize and increase the tunability of parametric oscillator;
- b) Apply the tunable IR parametric oscillator to monitoring and transmission measurements in the atmosphere.

Recent Progress:

A frequency doubled Nd-YAG laser has been built and used to pump a LiNbO_3 parametric oscillator. The pump uses internal doubling with LiIO_3 and a novel prism coupler to improve the conversion efficiency. The pump produces more than 1000 W in 200 n sec pulses at 5300 \AA in a very stable TEM₀₀ mode. An experimental and theoretical study of two pass harmonic generation using the prism coupler and the Nd-YAG laser is complete.

The LiNbO_3 parametric oscillator is single resonant and can be temperature tuned from 2.0 to 2.5μ . Linewidth and stability measurements are in progress.

A pulsed ion laser has been built and operated as a possible pumping source. Using xenon the laser can produce up to 2000 W pulses on several lines in the visible. The output has several transverse modes and the laser cannot be mode controlled without significant loss of power. Measurements of small signal gain on several lines were made. The pulsed ion laser does not appear useful for parametric oscillator pumping.

A theoretical study of angle tuned parametric oscillator pumping is complete and shows the limits of angle tuning as determined by the threshold increase due to the non-collinear interaction. The optimum cavity design for angle tuned oscillators is described.

References and Recent Publications:

1. "Threshold Calculations for Angle Tuned Parametric Oscillators", R. Basu and W. H. Steier, presented at the Optical Society of America Meeting, - Tucson, Ariz., April 1971.

2. "Bandwidth and Threshold Calculations for Angle Tuned Parametric Oscillators", R. Basu and W. H. Steier, IEEE Journal of Quantum Electronics (accepted for publication).
3. "Experimental Study of Two Pass Internal Second Harmonic Generation Using a Prism Coupling Technique", D. Gonzalez, S. Nieh, W. H. Steier (in preparation).

1.3 MAGNETISM

1.3.1 Magnetostrictive Behavior of the Si-Doped YIG

F44620-71-C-0007, The Joint Services Electronics Program

J. Smit and D. R. Mack

Objective:

The technical properties of ferrites, such as permeability, coercive force, switching time, resonance, microwave losses, etc., depend upon the coupling of the magnetic moment to the lattice. The objective of this task is to investigate the magnetostrictive behavior of Si-doped yttrium iron garnet (YIG).

Approach:

Strain guage measurements are made between 4°K and room temperature on a single crystal of Si-doped YIG in magnetic fields applied in various directions. The results are analyzed in terms of non-quenched orbital moments of the ferrous ions.

Recent Progress:

It was known that Si substitutions have a large influence on the magnetostriction of yttrium-iron garnet (YIG) at room temperature. We found that its effect is at least 10 times as strong at low temperatures, with a maximum, especially for the [110] direction, at about 80°K. Moreover, below 50°K a magnetic anneal effect occurs. This could all be quantitatively interpreted in terms of the divalent iron ions introduced by the quadrivalent Si ions. These Fe^{2+} ions have a non-quenched orbital angular momentum, which is strongly coupled to the lattice. At low T, these Fe^{2+} ions stay in the neighborhood of the Si^{4+} ions, but break away at higher T. This increases their magnetostriction, because the anisotropic perturbing fields of the Si ions then become less important. Good quantitative agreement between experimental and theoretical data for the anisotropy and the temperature dependence of the magnetostriction was obtained. Detailed results will be available in references cited below.

References and Recent Publications:

1. In preparation: "Magnetostriction in Silicon-Doped Yttrium Iron Garnet".
2. Dissertation: Daniel R. Mack, "Magnetostriction in Silicon- and Calcium-Doped Yttrium Garnet", Ph.D., 1972.

1.3.2 The Measurement and Analysis of Hyperfine Fields in
Magnetic Alloys and Compounds

F44620-71-C-0007, The Joint Services Electronics Program

J. Smit

Objective:

To measure internal magnetic moments in solids.

Approach:

Perform nuclear magnetic resonance experiments and measurements of the Mossbauer effect for information about the local magnetization and chemical composition of mixed ferrites as used in computers and microwave devices, and of segregated permanent magnet alloys such as Alnico.

Recent Progress:

The NMR study on Ni-based alloys was completed and published (see References below). The results provided information about the distribution of the excess electrons of the solute atoms over the neighboring atoms. The distribution appears to be very important not only for magnetic properties but also for many other properties such as the mechanical yield strength of similar alloys.

The experimental techniques and types of analysis used in this work will be applied to other alloys in the continuation of this project.

References and Recent Publications:

1. "Mossbauer Effect in Li-Zn Ferrites", J. Applied Phys., 42, 2344-48, 1971.
2. "Nuclear Magnetic Resonance in Ni-Cu, -Zn and -Ga Alloys", Solid State Communications, V 9, pp. 1880-1892 (1972).

1.3.3 Study of Paramagnetic Impurities in Anti-ferromagnetic Crystals

F44620-71-C-0007, The Joint Services Electronics Program

J. P. Hurrell

Objective:

To understand the fundamental microscopic and macroscopic properties of materials exhibiting second order phase transitions.

Approach:

Using the resonance properties of paramagnetic impurities to probe local fluctuations, crystal distortions and/or spin canting.

Recent Progress:

The well-localized resonance of a paramagnetic impurity (E_r) in specially grown antiferromagnetic MnF_2 . Associated with this impurity is a fairly stable charge compensation which must be dispersed before further detailed investigations can be performed. Paramagnetic impurities have also been observed in $TmAsO_4$ and $TmVO_4$ in their low temperature phases where they behave as Van Vleck paramagnets. In the arsenate, we have observed a rapid temperature dependence to the linewidth of an erbium resonance in the vicinity of the transition temperature which we hope to be able to correlate with fluctuations in the $TmAsO_4$ system. The natural defect center observed in the vanadate does not exhibit a similar line broadening. Consequently, we feel that the broadening reflects the effects of lattice distortions and not magnetic interactions.

References and Recent Publications:

1. "Strain-Induced Effects in the EPR Spectrum of $Dy^{3+}:YVO_4$ ", Bull. Am. Phys. Soc. 17, 49 (1972).
2. "Intensities of the Vibronic Sidebands of Sm^{2+} Fluorescence in BaF_2 : Theory and Experiment", Bull. Am. Phys. Soc. 17, 130 (1972).
3. "Nuclear Induced Electron-Spin-Echo Decay in Solids", Solid State Comm. 9, 461 (1971).
4. "Theoretical Survey of the Sidebands of Sm^{2+} Fluorescence in BaF_2 ", accepted for publication in Physical Review.

1.4 METALS, ALLOYS AND LOW TEMPERATURE PHYSICS

1.4.1 An Electron Microscope Investigation of Grain Boundary Phenomena During High-Temperature Creep

F44620-71-C-0007, The Joint Services Electronics Program

T. G. Langdon

Objective:

The occurrence of grain boundary sliding in polycrystalline materials during high-temperature creep leads to crack formation and premature fracture. This research program will investigate grain boundary phenomena using transmission electron microscopy.

Approach:

High-temperature constant stress creep tests will be terminated at selected strains and the specimens sectioned for examination by transmission electron microscopy. Emphasis will be placed on the formation of substructure and the development of grain boundary dislocations.

Recent Progress:

This is a new project, however, the following recent activities have occurred in preparation for formal initiation:

- a) Equipment: A 20,000 pound Instron testing machine has been obtained which is one of several important items of equipment needed for the research. The machine will allow tests at constant strain rate in addition to the constants stress to include crack formation under dynamic high strain-rate conditions.
- b) Preliminary theoretical work concerning:
 - 1) The nature of creep mechanisms in hexagonal materials and the shape of the strain: time curves.
 - 2) The significance of grain boundary sliding under conditions of low-stress creep, and in particular, the application of computer techniques to determine the stress dependence of sliding.

1.4.2 Experimental Investigation of the Electronic Structure
of Intermetallic Compounds and Transition Metals

F44620-71-C-0007, The Joint Services Electronics Program

M. H. Halloran, J. H. Brewer and R. D. Parker

Objective:

To carry out experiments on: AuIn_2 to determine the similarities and differences of its electronic structure as compared to AuGa_2 ; on MgZn_2 to determine its electronic structure; and, on vanadium to determine the extent of its electronic similarity to Nb and Ta.

Approach:

The deHaas-van Alphen effect will be used in a superconducting solenoid at temperatures as low as 1.1°K and magnetic fields as large as 100 kOe. Using uniaxial stress up to 2 kilobars when appropriate, the Fermi Surface topologies will be determined for the materials.

Recent Progress:

The experimental research on AuGa_2 and AuIn_2 is essentially complete, and one publication appeared during the last year. The Fermi surfaces of AuIn_2 and AuGa_2 are very similar with a few very significant differences which are consistent with the modifications to the nearly Free Electron Model which have been calculated in an APW band structure calculation. All the observed sections of Fermi surface can now be attributed plausibly to the calculated models, which in turn yield a possible explanation for the anomalous temperature dependence of the magnetic properties of AuGa_2 .

The experimental results on vanadium are in progress and should be completed in mid 1972. Early results confirm the expectations that vanadium should have a Fermi surface similar to niobium and tantalum. Experiments have been performed on dendritic crystals grown by the Bureau of Mines and on zone-refined crystals grown in our laboratories, with the latter giving slightly better results so far.

The results on MgZn_2 are very preliminary at this time. Samples have been grown with resistance ratios of approximately 200

$\left(\frac{R_{293}}{R_{4.2}}\right)$, and very large signals have been obtained using the dHvA effect.

References and Recent Publications:

1. "The Fermi Surface of Vanadium", by R. D. Parker, J. C. Abele and M. H. Halloran, Bull. Am. Phys. Soc. 16, 838, August 1971, Seattle, Washington.
2. "New Fermi Surface Observations in AuIn₂", by J. H. Brewer and M. H. Halloran, Bull. Am. Phys. Soc. 17, 92, January 1972, San Francisco.
3. Articles Published:
 - a) "New Fermi Surface Results in AuGa₂", by J. C. Abele, J. H. Brewer and M. H. Halloran, Solid State Comm. 9, 977 (1971).

1.4.3 Thermoelectric Properties of New Materials in Metastable Crystalline and Amorphous States

F44620-71-C-0007, The Joint Services Electronics Program

R. Wang

Objective:

The synthesis and characterization of new amorphous and metastable alloys with high potential of good thermoelectric performance.

Approach:

To synthesize new amorphous solids and metastable crystalline phases by rapid quenching from liquid state; to measure the electronic and thermoelectric properties of structure-sensitive properties.

Recent Progress:

A number of tellurium-based semiconducting amorphous materials (Te-In, Te-Ga, Te-Ge) have been prepared by rapid quenching alloys from the liquid state. All amorphous phases are characterized by x-ray diffraction and electron microscopy.

The thermoelectric power of an amorphous In₂₀Te₈₀ alloy was measured from 80°+ to 300°K. At high temperatures electrons are excited thermally across the gap and the Fermi level will lie near the middle of the gap. The thermoelectric power measurements show the intrinsic type increasing as temperatures decrease.

After annealing at 100°C for 16 hours the samples become crystalline. The thermoelectric power then decreases an order of magnitude, and the high temperature intrinsic region shifts to higher temperatures. In some cases the low temperature drag effect occurs.

Electric resistivity and Hall mobility measurements are in progress but accurate data on the Hall measurements will be difficult to obtain due to amorphous low mobility carriers.

We have found, for the first time, a memory switching effect in the In-Te, Ga-Te and Ge-Te amorphous semiconducting materials. The switching characteristics and mechanism are now under investigation.

References and Recent Publications:

1. In preparation: "Thermoelectric Properties of Te-Based Amorphous Semiconductors".

1.4.4 Properties of Electronic Materials and Devices at Low Temperatures

F44620-71-C-0007, The Joint Services Electronics Program

T. I. Smith, Y. B. Kim and M. D. Daybell

Objective:

To study the electronic properties of particular materials at temperatures of 4°K and below, with the intent of utilizing these materials in instrumentation and communications devices operating at these temperatures. It is expected that significant improvement in many such devices will be realized by operating at low temperatures.

Approach:

The measurements fall into two categories. In the first, data will be obtained through measurement of the microwave surface impedance of the materials, using cavities and high frequency transformer configurations. In the second, we will measure the properties of conventional solid state devices operated at low temperatures. Quantities such as device noise, gain, and operating power level are important.

Recent Progress:

The initial efforts in this new project involve measuring the loss tangent of very low loss dielectric materials needed to support devices inside high Q, superconduction microwave cavities.

1.4.5 The Effects of Electric and Magnetic Fields and Other Physical Parameters on the Nucleation, Structure, and Residual Properties of Vapor-Deposited Metal Films
AT(04-3)-113, Project 22, Atomic Energy Commission

L. E. Murr, O. T. Inal, M. C. Lin, H. P. Singh,
H. R. Vydyanath, and G. I. Wong.

Objective:

To determine whether electric or magnetic fields applied parallel to or perpendicular to a substrate during vacuum-deposition can significantly alter the nucleation and growth of their metal films.

Recent Progress:

This 3 year project was completed at the close of the reporting period. Detailed results are contained in the cited publications summarized as follows.

During the past year, the effects of electric fields on the nucleation and growth of In, Sn, Bi, Pb, Cd, Au, and Ag thin films was continued, with particular emphasis on the low-melting point metals. No effects were observed with carefully defined potential gradients ranging up to 3 KV/cm in the plane of the substrate. During the course of these investigations, several prominent nucleation characteristics were observed. These included vapor-liquid-solid (liquid nuclei supercooling) and vapor-solid nucleation characteristics which were observed to be a function of substrate temperature and film thickness evaporated at 10^{-6} Torr vacuum. Detailed analyses were made of the effects of substrate temperature, evaporation rate, and film thickness on nucleation, film growth, and continuity for Au, Ag, Pd, Pt, In, Sn, and Al. The results indicated the substrate temperature/melting temperature to be a critical factor in film growth, and to influence film continuity as a function of mean foil thickness, in addition to the surface energy of the nuclei, and the energy of the substrate/overgrowth interface.

A special apparatus was constructed for the application of a magnetic field in the plane of a substrate, having a linear field capability of 0-4 Kgauss. Films of Ni, Co, and Fe grown under these field conditions at a range of substrate temperatures showed no effect of a magnetic field in a vacuum of 10^{-6} Torr.

Detailed examinations of Pt overgrowths on Mo W Ir field emitter end form substrates by field-ion microscopy indicated the very early stages of nucleation and film growth to be characterized by an accommodation of the overgrowth specie to the crystallography of the substrate

(basal-plane pseudomorphism). Evidence obtained suggests that the overgrowth reverts to its habit crystallography at some critical thickness (usually only about 10-20 atom layers in mean thickness), and this relaxation can be accompanied by the introduction of crystal defects.

This investigation has shown that the enhancement of thin film growth-- viz., grain size control, the production of large grain or single-crystal thin films, is not significantly influenced by an electric field applied parallel or perpendicular to the substrate during evaporation for linear and reasonably homogeneous field strengths up to 10^3 volts/cm. The dominant parameter influencing film growth is observed to be the substrate temperature, particularly the substrate temperature/melting temperature ratio. No significant enhancement of grain size in ferromagnetic thin films has been observed for field strengths up to 7 Kgauss applied perpendicular to the substrate, and up to 4 Kgauss applied parallel to the substrate plane.

Recent Publications:

1. L. E. Murr, "Structure and Energetics of Vapor-Deposited Indium Films," *Phys. Stat. Sol. (a)*, 1, 487 (1970).
2. G. Wong and L. E. Murr, "Structure of Palladium Single-Crystal Films Prepared by Flash Evaporation onto (001) NaCl Substrates," *Proc. EMSA*, C. J. Arceneaux (ed), Claitor's Publishing Div. (Baton Rouge), p. 456 (1970).
3. K. P. Staudhammer and L. E. Murr, "Thermally Activated Nucleation and Faceting in Immiscible Cu-Cr Thin Films," *Ibid*, p. 518.
4. L. E. Murr, "Effects of Substrate Temperature, Pressure, and High Evaporation Rates on Nucleation, Epitaxy and Structure of Palladium Thin Films," *Thin Solid Films*, 7, 101 (1971).
5. H. P. Singh and L. E. Murr, "Nucleation and Growth Characteristics of Palladium and Indium Thin Films," *WESTEC 1971*, ASM Technical Paper W71-12.6, 10 pp. (1971).
6. K. P. Staudhammer and L. E. Murr, "Electron Microscopy of Thin Film Immiscible-Miscible Systems," *Proc. EMSA*, C. J. Arceneaux (ed.), Claitor's Publishing Div. (Baton Rouge), p. 218 (1971).
7. L. E. Murr, O. T. Inal and H. P. Singh, "Nucleation and Epitaxial Growth of Vapor-Deposited Films, Electron Transmission and Field-Ion Microscopy Studies," *Ibid.*, p. 214.
8. G. I. Wong, H. P. Singh and L. E. Murr, "Electron Diffraction Effects in Multi-Layered (Overlapping) Palladium Single-Crystal Films," *Ibid.*, p. 190.

9. H. P. Singh and L. E. Murr, "Nucleation and Growth Characteristics of Thin Metal Films," Ibid., p. 216.
10. L. E. Murr, O. T. Inal and H. P. Singh, "A Field-Ion Microscope Study of Vapor-Deposited Platinum," Thin Solid Films, 9, 241 (1972).
11. H. P. Singh and L. E. Murr, "Nucleation and Growth Characteristics of Palladium and Indium Thin Films," Met. Trans., April (1972).
12. H. P. Singh and L. E. Murr, "Activation Energy and Saturation Density for In and Sn Thin Films on NaCl Substrates," Scripta Met., April (1972).
13. H. P. Singh and L. E. Murr, "Electron Microscopy of Nucleation and Growth of Indium and Tin Films," Phil. Mag. (1972), in the press.
14. L. E. Murr and H. P. Singh, "Significance of Electric Fields on the Growth of Thin Metal Films," submitted to Appl. Phys. Letters.
15. H. P. Singh and L. E. Murr, "An Electron Microscope Study of Vapor-Liquid-Solid Growth in In and Sn Thin Films," Proc. EMSA, C. J. Arceneaux (ed), Claitor's Publishing Div. (Baton Rouge) (1972).

1.4.6 Measurement of Interfacial Energies in Solid State
Metals and Alloys

N00014-67-A-0269-0010, Office of Naval Research

L. E. Murr, R. J. Horylev, O. T. Inal, W. N. Lin,
 G. I. Wong

Objective:

To clarify points raised concerning the temperature coefficients for interfacial free energies in an alloy system by a detailed, systematic measurement of the surface, grain boundary, and coherent twin boundary free energies in 304 stainless steel over a range of elevated temperatures.

Recent Progress:

This work will be completed upon publication of the final report cited below. The following abstract of the report describes the work and results for the full contract period.

The method of zero creep of small diameter 304 stainless steel wires

coupled with scanning and transmission electron (shadowgraphic) microscopy of grain boundary-surface intersection grooves was used to measure average values for the surface free energy, F_S , and the grain boundary free energy, γ_{gb} , at temperatures of 1060, 1160, 1260 and 1360°C, from which the temperature coefficients of the specific interfacial free energies, dF_S/dT and $d\gamma_{gb}/dT$ were measured to be -1.760 and -0.890 ergs/cm²°C respectively. Mean values of coherent twin boundary free energy/grain boundary free energy ratios, γ_{tb}/γ_{gb} were determined for low-torque twin-grain boundary intersections in thin foils of 304 stainless steel using techniques of transmission and diffraction electron microscopy as 0.016, 0.017, 0.024, and 0.024 at 910, 985, 1969 and 1180°C, and values of γ_{gb} substituted at temperatures from the measured values of γ_{gb} to obtain average coherent twin boundary free energies at temperature. From this data, the temperature coefficient of twin boundary free energy was determined to be +0.007 ergs/cm²°C. By assuming the temperature coefficients measured at elevated temperatures to extend linearly to room temperature, room temperature (25°C) values of $F_S = 3975$ ergs/cm², $\gamma_{gb} = 1670$ ergs/cm², and $\gamma_{tb} = 10$ ergs/cm² were obtained; and the room temperature value of stacking-fault free energy, γ_{SF} , was determined to be 20 ergs/cm² by multiplying γ_{tb} by a factor of 2. The differences in sign for the temperature coefficients of surface and grain boundary free energies compared with the temperature coefficient of twin boundary free energy suggests a phenomenologically different segregation thermodynamics at these interfaces.

The techniques of transmission electron microscopy have been employed in a study of coherent annealing twins and their energetics in ultra-pure aluminum. Coherent twin boundaries have been unambiguously identified, and grain-corner twins in aluminum observed for the first time. A value of $\gamma_{tb}/\gamma_{gb} = 0.23$ at 450°C was obtained for pure aluminum.

Details of the results are obtained in the final report and publications listed therein. In addition, the final report expands and discusses the use of techniques developed in this investigation for the measurement of interfacial free energies in connection with composite and dispersion-hardened systems. Particular emphasis on techniques of scanning electron microscopy are presented.

References and Recent Publications:

A full list of publications is contained in the following final report which can be obtained from the National Technical Information Service or the Defense Documentation Center:

L. E. Murr, "Measurement of Interfacial Energies in Solid State Metals and Alloys," USCEE Report No. 417, July 1972.

1.4.7 Influence of Stress on Precipitation and Coarsening
in Alloys

AFOSR-71-2087, Air Force Office of Scientific Research

S. M. Copley

Objective:

To achieve a more complete understanding of the effect of stress on solid state processes and its concomitant effect on microstructure and properties by studying the effect of applied and residual stresses on precipitation and coarsening in several alloy systems including:

- (1) titanium-base superconducting alloys
- (2) nickel-base alloys
- (3) Alnico permanent magnet alloys
- (4) unidirectionally solidified eutectic alloys

Approach:

To apply a uniaxial stress to alloy specimens as they are cooled through their solvus temperature or are aged at a temperature suitable for coarsening. Residual stresses are controlled by alloying. The resulting microstructures are determined by transmission electron microscopy. Particular attention is being given to the possibility of employing "stress aging" to produce alloys with novel microstructures and properties.

Recent Progress:

In the past year, much progress has been made in achieving the goals outlined in our initial proposal. All equipment needed to carry out the proposed research has been fabricated or purchased, with the exception of the induction melting and crystal growing facility to be completed this fall. Arc melted buttons of several Ti-base and nickel-base alloys have been prepared. Transmission electron microscopy has been employed to determine precipitate morphologies of these alloys aged normally and aged under an applied stress. A theoretical study is nearly completed that predicts the morphology of coherent precipitates in alloys after both normal aging and stress aging, which takes into account such factors as lattice misfit, elastic inhomogeneity, elastic anisotropy, volume fraction of precipitate, precipitate size and interphase boundary energy. A further theoretical study is nearly completed that predicts the amount of stress induced segregation that can occur in multi-component systems subjected to an applied uniaxial stress.

References and Recent Publications:

1. S. M. Copley, "Application of Continuum Elastic Models to Transformations in Solids", presented at the Symposium titled "Effect of Stress on Reactions in Solids", 4th Annual Spring Meeting of The Metallurgical Society of AIME, Boston, Mass., May 8, 1972.
2. G. H. Narayanan and S. M. Copley, "A Composite Model for Characterizing Residual Strains in Alloys with Coherent Precipitates", in preparation.
3. M. Menon and S. M. Copley, "Stress Induced Segregation in Binary Alloys", in preparation.
4. S. M. Copley, "The Effects of Interface Coherency on the Morphology and Properties of Metallic Composites", an invited paper to be presented at a Symposium on Interfacial Bonding and Fracture in Polymeric, Metallic and Ceramic Composites, November 1972, sponsored by the American Chemical Society and U.C.L.A. The proceedings will be published in The Journal of Adhesion. A hard cover version will be published by Gordon and Breach, Science Publishers, Inc.

1.4.8 Materials Research on High Field Superconductors and Rare Earth Cobalt Magnetic Materials

GH-34652, National Science Foundation

AT(04-3)-113, #23, Atomic Energy Commission

Y. B. Kim, R. Wang, and J. Savage

Objective:

To investigate the metallurgical microstructure in relation to the superconducting properties of high field superconductors and the coercive forces of rare earth cobalt magnetic materials.

Approach:

As for the superconducting materials, we have developed powder sintered compacts in which Nb_3Sn powder particles are dispersed in copper matrix. The ac losses of such superconducting materials may be significantly lower than in the conventional multi-filament superconducting cables. The metallurgical aspects of these sintered compacts have already been described in the last progress report (#14), and currently the measurements of ac losses in these materials are being carried out.

Recent Progress:

By applying the rapid quenching technique to rare earth cobalt magnetic materials, we have obtained coercive forces much larger than attainable by the conventional methods. The PrCo_5 and $(\text{MM})\text{Co}_5$ powders obtained by splat cooling are found to have very large coercive forces. Small grains of $1-5\mu$ in size are produced in particles of $1-40\mu$. Simple binding of these particles under ~ 27 kOe leads to coercive fields as large as 9 kOe for PrCo_5 and 5 kOe for $(\text{MM})\text{Co}_5$, which are higher than the largest values reported for the conventionally fabricated magnets. The SmCo_5 powders made by this process, however, do not yield a larger coercive field. In splat cooling, particles are subject to much less surface defects than that encountered in the conventional grinding process. Also, some degree of preferential growth of the grains appears to result from the high thermal gradient between the liquid alloy and the substrate. In addition, a second phase was found to form surrounding the RCo_5 phase, which may have improved the surface properties of the RCo_5 phase. Since the presence of the second phase has been shown to have advantages to the sintering process for some high quality magnets of SmCo_5 and PrCo_5 , it is expected that liquid sintering of fine powders prepared by this new process would lead to greater improvement of magnetic properties (see Reference a).

References and Recent Publications:

1. R. Wang, K. S. Kim, and Y. B. Kim, "Preparation of Fine Powders of Rare Earth Cobalt by Rapid Quenching Technique," presented at the 1972 InterMag Conference, Kyoto, Japan.

1.4.9 Ultra-Low Temperature Studies of Superconductors and Magnetic Alloys

GP-29031, National Science Foundation

Y. B. Kim, M. D. Daybell

Objective:

- I. Understanding of the properties of magnetic alloys from an interacting local moment viewpoint.
- II. Investigation of fluctuation dominated properties of type II superconductors.

Approach:

- I. Properties of isolated local moments and pairs of local moments in a metal are determined from magnetic and transport properties of alloys in the temperature range where phonons are frozen out.
- II. Microwave impedance and other transport properties of type II superconducting alloys are examined down to very low temperatures and up to fields 50 kilogauss.

Recent Progress:

Investigation on the interaction between magnetic impurities (interaction between Kondo systems) in zero external magnetic fields has been described in the previous progress report (#14). Work is continuing to extend this investigation in the presence of external magnetic fields.

In order to resolve the long-standing controversy between the Caroli-Maki theory and the Thompson theory, we have measured the microwave surface resistance of various Nb-Ta and Pb-In superconducting alloys using a derivative technique to determine its rate of change with field near H_{C2} . Previous dc measurements of this slope have generally been interpreted to show agreement with the Caroli-Maki theory, which Thompson has found to be incomplete. Measurements of the derivative of the normalized surface resistance of samples of dirty type II superconductors with respect to the magnetic field, compare favorably with the theoretical predictions of Thompson when the measured values of the derivative are extrapolated to H_{C2} . If the derivative is obtained from the region below the transition where its value is relatively constant, results which support the Caroli-Maki theory are obtained. Data collected without the benefit of the derivative technique would tend to yield such results. However, the data obtained by an appropriate extrapolation in the immediate vicinity of H_{C2} support the Thompson correction to the Caroli-Maki theory (Reference a).

References and Recent Publications:

1. R. J. Pedersen, Y. B. Kim, and R. S. Thompson, "Microwave Surface Resistance of Type II Superconductors in the Vortex State", submitted for publication in Physical Review, 1972.

1.5 SOLID STATE DEVICES

1.5.1 Solid State Microwave Devices

F44620-71-C-0007, The Joint Services Electronics Program

H. L. Stover, G. T. Culbertson, B. J. Gordon

Objective:

To investigate present devices for new understandings and to investigate fabrication and assembly of new devices both leading to better microwave devices; to provide service work to other research groups.

Approach:

To fabricate microwave devices directly from raw materials using new techniques; grow high-quality epitaxial silicon, assemble multiepitaxial devices, and study old and new devices over wide frequency ranges.

Recent Progress:

Much work was devoted to mastering some of the peripheral processes and the fabrication and installation of equipment. All the technologies developed in the laboratory over the past several years were merged to successfully fabricate and test a Punched-Through Injection Transit-Time Microwave Oscillator. Theoretical results have indicated that the device, by virtue of its low noise, will make a significant mark on the microwave semiconductor device field. Several characteristics of the oscillator are such that it could potentially supplant IMPATT and Gunn devices in many applications. Several different oscillator structures were fabricated, each potentially more efficient.

The laboratory facilities continue to provide service work for other research groups as well as to study new devices and techniques.

References and Recent Publications:

1. "A Punch Through Injection Diode: A New Microwave Source and Technology Related to Its Fabrication", G. T. Culbertson, Ph. D. Dissertation, 1972; reviewed during the February 1972 JSEP meeting at USC.
2. "I-V Characteristics of Punched-Through Injection Microwave Oscillator", B. J. Gordon and H. L. Stover, in preparation.

1. 5. 2 Microwave Acoustic Devices

N00014-67-A-0269-0018, Office of Naval Research

F44620-71-C-0007, The Joint Services Electronics Program

K. M. Lakin

Objective:

The Microwave Acoustic and Solid State Device Laboratory is directed toward a complete investigation of acoustic wave propagation, materials growth and evaluation, and a study of acoustoelectric device physics using surface elastic waves.

Approach:

By theoretical analysis of wave propagation and interactions with semiconductors and by experiments performed on surface wave delay lines and amplifiers.

Recent Progress:

Improvements have been made in the computer programs to increase the computation speed and accuracy for surface wave boundary value problems. An extensive analysis of surface waves on sapphire was carried out. The case of ZnO epitaxial films on R plane sapphire was computed and the existence of a new high coupling constant layered mode was verified quantitatively. This new mode should increase the efficiency of signal processing devices and will be examined in greater detail.

Epitaxial films of AlN and R plane sapphire were grown with improved surface finish and quality. This material was used to make a 400 MHz surface wave delay line. This high velocity material combination is being further evaluated for signal processing devices at 1 GHz where larger device bandwidth are obtainable. In addition, silicon-on-sapphire films have been grown and research is continuing in an effort to improve the semiconducting properties.

1. 5. 3 Ultrahigh Frequency Stable Signal Sources

F44620-71-C-0007, The Joint Services Electronics Program

K. M. Lakin

Objective:

To study a new technique for obtaining stable ultrahigh frequency crystal controlled oscillators. The research would involve a study of both materials and devices employing surface wave delay lines.

Approach:

Surface wave delay lines will be employed as feedback elements in a large multiple 2π phase shift oscillators. The temperature coefficient properties of useful piezoelectrics will be examined both theoretically and experimentally to obtain "fundamental mode" oscillations up to 1 GHz.

Recent Progress:

This is a new JSEP task proposed on the basis of initial theoretical and experimental results at 100 MHz obtained under the broad task "Microwave Acoustic Devices" as described in the preceding article.

Recently we have used a surface wave delay line to phase lock a laboratory voltage controlled signal generator as a preliminary step in the research. In addition, the phase locked loop has been found useful for evaluating the temperature properties of materials for other than oscillator applications such as tapped delay lines.

1.6 DEFECT CHEMISTRY AND SOLID STATE ELECTROCHEMISTRY

1.6.1 High Temperature Defect Chemistry of Al_2O_3

F 33615-72-C-1123, U.S. Air Force (AFSC)

F. A. Kroger, A. Deganin, B. V. Dutt, and J. Yee

Objective:

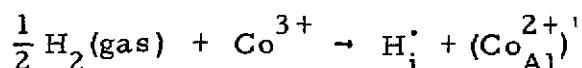
To determine the defect structure of pure and doped sapphire.

Approach:

- High-temperature conduction studies of Al_2O_3 , pure and undoped with Mg, Co, Ti.
- Electromotive force measurements on cells $\text{Pt}, \text{O}_2 | \text{Al}_2\text{O}_3 | \text{Pt}, \text{air}$ and cells $\text{W}, \text{H}_2, \text{H}_2\text{O} | \text{Al}_2\text{O}_3 | \text{W}, \text{H}_2, \text{H}_2\text{O}$.
- Measurement of absorption and electron spin resonance on Al_2O_3 -Co with cobalt in various valency states (2+, 3+).

Recent Progress:

Emf measurements on cells $\text{Pt}, \text{O}_2 | \text{Al}_2\text{O}_3 | \text{Pt}, \text{air}$ have shown that the ionic transference number $t_i = 1$ up to 1450°C . The valency of cobalt can be changed from 3+ to 2+ and V.V. by heating in $\text{H}_2 + \text{H}_2\text{O}$ and air, respectively at 1500°C . Since heating in a low $p\text{O}_2$ (e.g., a CO-CO₂ mixture) does not have the same result, this indicates that H is entering the crystal.



Presently measurements are being carried and on Al_2O_3 in H_2 , viz.,

- conduction
- emf of cells $\text{W}, \text{H}_2, \text{H}_2\text{O} | \text{Al}_2\text{O}_3 | \text{W}, \text{H}_2, \text{H}_2\text{O}$.

From the latter, both $t_i \equiv t_{\text{Al}}$ and t_{H} , the proton transference number can be determined.

$$E = - \frac{kT}{q} \int \left\{ t_{\text{Al}} d \ln p_{\text{H}_2\text{O}}^{-1/2} + (t_{\text{Al}} + t_{\text{H}}) d \ln p_{\text{H}_2}^{1/2} \right\}$$

Present results indicate that both t_{Al} and $t_{\text{H}} > 0$. At $T > 1600^\circ\text{C}$, the valency of Co can be changed in the absence of H_2 . Electron spin resonance

shows the signal due to Co^{2+} increasing with decreasing $p\text{O}_2$. Optical absorption shows a corresponding increase in Co^{2+} absorption peaks and a decrease in Co^{3+} absorption. Attempts are being made to make the measurements quantitative, i.e., determine oscillator strength. Then absorption strength will give $[\text{Co}^{2+}]$ and combination with conduction

$\sigma = C_{\text{Al}}^{3+} q \mu_{\text{Al}}$ with $C_{\text{Al}_i^{3+}} = \frac{1}{3} C_{\text{Co}^{2+}}$ gives μ_{Al} , the mobility of interstitial Al with a greater accuracy than we have now.

References and Recent Publications:

1. R. J. Brook, J. Yee, and F. A. Kroger, "Electrochemical Cells and Electrical Conduction of Pure and Doped Al_2O_3 ," J. Am. Ceram. Soc. 54, 444-451 (1971).

2. PLASMAS AND APPLIED ELECTROMAGNETICS

2.1 Radiation, Waves and Transport Properties in Plasmas

GK24877, National Science Foundation

H. H. Kuehl

Objective:

To obtain an understanding of the near fields and input impedance of radio frequency probes or antennas in warm magnetized plasmas.

Approach:

The theory is based on the Boltzmann equation using the electrostatic approximation to obtain simple results. Measurements are performed on small probes or dipoles in a pulsed r.f. discharge using argon gas.

Recent Progress:

A theory has been derived for the input impedance of a short, cylindrical dipole antenna immersed in a warm anisotropic plasma which is described by the kinetic theory (Boltzmann equation). For a dipole oriented parallel to the static magnetic field, the input impedance is obtained as a one-dimensional integral suitable for numerical integration. Under certain conditions, the integral can be evaluated giving analytical formulas valid near the second and third electron cyclotron harmonics. The results show new contributions to the input impedance due to the excitation of cyclotron harmonic waves which propagate near the harmonics of the cyclotron frequency. These effects are not predicted by either the cold or hydrodynamic theories.

Impedance measurements have been performed on a dipole immersed in a pulsed, r.f. discharge, argon plasma. The effects of the plasma sheath are found to be very important. The experimental results show that the input impedance undergoes frequency passes through the harmonics of the electron cyclotron frequency which is in agreement with the predictions of the theory.

References and Recent Publications:

1. H. H. Kuehl and A. L. Peratt, "Transmission and Reflection of a Wave Obliquely Incident on a Nonuniform Magnetized Plasma", Radio Sci. 7, 309 (1972).

2. H. H. Kuehl and A. L. Peratt, "The Plasma Capacitor in a Magnetic Field", Phys. Fluids 15, (1972).

2.2 Integral-Equation Analysis of Axially Symmetric Reflectors

F44620-71-C-0007, The Joint Services Electronics Program

W. V. T. Rusch

Objective:

Solution of the problem of scattering from axially-symmetric bodies using moment techniques to solve the appropriate integral equation for the particular problem.

Approach:

Application of numerical techniques to invert Maue's Integral Equation for the currents on an axially symmetric reflector.

Recent Progress:

Maue's integral equation has been formulated for scattering from a surface of revolution with a linearly-polarized incident spherical wave. The equations have been converted into linear, algebraic matrix equations. These matrix equations have been inverted using a computer program which has been debugged and checked out using comparisons with classical scattering results for a perfectly conducting sphere. The program has been applied to scattering from a hyperboloidal subreflector in a Cassegrainian feed system. The results do not appear to converge as the subreflector thickness vanishes. This is an intrinsic property of an H-field integral equation.

Attention has been focused on the E-field integral equation for the same geometry. This equation has a somewhat less diagonally-dominant system matrix. However, it is less subject to convergence problems in the case of vanishing reflector thickness. This program is also programmed, using a program developed by Mautz. The program has been checked out for a sphere, but some difficulties are being experienced when applying it to a hyperboloid. Work is continuing on this aspect of the problem.

References and Recent Publications:

1. "Net-field Polarization in a Magnetically Biased Plasma", by W. V. T. Rusch and C. T. Stelzried, has been revised and resubmitted to Radioscience.

2. "Applications of Source Multipole Expansions to Simplify Reflector Antenna Calculations", by W. V. T. Rusch; presented as a seminar at UCLA on May 23, 1972, and to be submitted to URSI/GAP Symposium in December, 1972.
3. "Scattering from a Surface of Revolution Using Integral Equations", Engineer's Thesis in preparation by H. Arain.
4. "Evaluation of the Equivalent Paraboloid Concept", paper in progress by W. V. T. Rusch and R. Booth.
5. "Radiation from a Paraboloid with an Axially Defocused Feed", by P. T. Ingerson and W. V. T. Rusch, paper submitted to IEEE Transactions on Antennas and Propagation.

3. ELECTRICAL ENGINEERING SYSTEMS AND INFORMATION SCIENCES

3.1 CONTROL SYSTEMS

3.1.1 Basic Studies in Traffic Responsive Control Systems GK 24520, National Science Foundation

N. E. Nahi and H. J. Payne

Objective:

To develop methods for the design of freeway traffic surveillance and control systems.

Approach:

To develop a mathematical model representing traffic flow on freeways and use this model to derive optimum control algorithms. Further, to derive optimum procedures for estimating traffic variables such as average car speeds and car density associated with any section of the road.

Recent Progress:

a) Models of Freeway Traffic. We have developed two distinctly different types of traffic models which provide complementary tools for our research on control and estimation algorithms. The first of these is a microscopic model, implemented on a digital computer, in which movements of individual vehicles are followed.

The second model developed is an aggregate variable model. In this model, the freeway is considered to consist of continuous sections with uniform geometric features, each of length approximately 1/2 mile; the variables of the model are the density and mean speed of vehicles in each section and the flow rate past boundaries of the sections. This model provides a capability of simulating an extended segment of freeway for several hours with relatively small computational expense.

b) Regulation of Freeway Traffic. Assuming nominal conditions on a freeway, e.g., those determined from the aggregate variable model using fixed ramp metering rates, one can obtain a linearized aggregate variable model whose variables are perturbations from nominal values. We have

taken as the objective of freeway regulation the maintenance of these nominal conditions. This can be achieved by selecting controls (adjustments in ramp metering rates) which minimize a cost expressed as a quadratic form in the perturbation variables. Suboptimal controls (i.e., those which nearly minimize this cost) have been determined with the desirable structural feature that each on ramp metering rate is determined by traffic conditions in a local segment of the freeway (of length typically 2-3 miles). This design method will be used to develop on ramp control software in the experimental Hollywood Freeway project.

Results of this research have been and will be reported in references.

c) Estimation of Traffic Variables. The basic aggregate traffic parameters are section mean-speed and section density. These are defined as the average of instantaneous speeds of automobiles in a specific section of the road, and the number of vehicles per lane-mile in that section, respectively. A direct measurement of these variables is usually very complicated and clearly not feasible as part of a real time traffic control or surveillance procedure. Such measurements, however, can be made and may, for instance, take the form of processing successive visual images of the road section through aerial photography. The complexity of this required processing makes procedures of this type infeasible for real time operation.

The alternative is to perform local measurements at various spatial intervals along the road and utilize this information to estimate the section mean-speed and section density. The most common local measurement device in use today is the so called "presence-detector". This device produces an output which is proportional to the time a vehicle is located above the location of the sensor (typically a 6' x 6' square in each lane of a road).

During the course of the present grant, optimal section mean-speed estimators and section density estimators were determined. These estimators are designed to utilize the information content of the output of the presence detectors located upstream of traffic at the beginning of the section. The estimators are of recursive nature and directly operate on the output of the presence-detectors. Consequently, they can be implemented very simply and in real time. The performance of the estimators was evaluated using (1) a car following simulation and (2) actual data derived from aerial photographs. The results of this study appear in detail in reference, a copy of which is attached to this proposal. The results, both from the point of view of simplicity of the estimators and quality of the estimates are very encouraging.

References and Recent Publications:

1. Isaksen, L., and H. J. Payne, "Regulation of Freeway Traffic", submitted to IEEE Trans. Automotive Control.

2. Payne, H. J., "Models of Freeway Traffic and Control", Simulation Council Proceedings, Vol. 1 (Mathematical Models of Public Systems), Chapter 6.
3. Mikhalkin, B., H. J. Payne, and L. Isaksen, "Estimation of Speed from Presence Detectors", to appear in the Highway Research Board Record, Freeway Operations.
4. Nahi, N. E., and Trivedi, A., "Recursive Estimation of Section Mean Speed and Density", USCEE Report No. 414, The Electronics Sciences Laboratory, University of Southern California (1972).

3.1.2 Studies of Large Scale Linear Systems

F44620-71-C-0007, The Joint Services Electronics Program

H. J. Payne

Objective:

To develop techniques to take advantage of invariance properties of large-scale linear systems.

Approach:

The studies will relate invariance properties of the underlying physical system to exploitable algebraic structure of the linear system model.

Recent Progress:

Linear dynamic systems with a periodic structure can be described by equations of the form

$$\begin{aligned}\dot{x} &= Ax + Bu \\ y &= Cx\end{aligned}$$

in which A , BB' and $C'C$ are circulant matrices. The optimal regulation of such systems is then specified by

$$u = B'Px$$

in which P is a circulant solution of the algebraic Riccati equation

$$PA + A'P - PBB'P + C'C = 0$$

These notions have been generalized to include matrices consisting of blocks of circulants.

The circulant properties can be exploited to yield a set of low order Riccati equations whose solutions provide the desired optimal regulator. This reduction in order has been shown to result in considerable computational savings in solving the algebraic Riccati equation.

This work was reported in the reference cited below and is considered to be complete. Extensions of the methodology employed here to generalized Toeplitz systems are being considered.

References and Recent Publications:

1. H. J. Payne, "Circulant Solutions of the Riccati Equation", submitted to IEEE Control Systems Society Transactions.

3.1.3 Input-Output Structure of Linear Systems

DA-ARO-D-31-124-71-G48, U.S. Army Research
Office - Durham

L. M. Silverman and B. C. Moore

Objective:

The main objective of this project is to characterize the input-output mapping properties of multi-input, multi-output linear systems and to apply these characterizations to various synthesis problems of control, estimation coding, etc., which involve systems which can be modeled appropriately.

Approach:

The basic approach is to utilize the structure algorithm developed by the principal investigator as a means of characterizing various quantities associated with a linear system. This has proved successful in attacking such problems as system inversion, input-output decoupling and model matching.

Recent Progress:

During the reporting period work was completed on the general model matching problem [1]. A necessary and sufficient condition was found for determining when an existing system can be dynamically compensated so that it has the same input-output response as some desired model and a procedure based on the structure algorithm for designing the required compensation was given. One potential application area for these results is in flight simulation where it is desired to compensate an existing

aircraft so that it flies like an as yet unbuilt one.

Another problem presently being considered is that of characterizing the "zeros" of a multi-input multi-output system. Such "characterizing atoms are important in many system problems. For the class of systems which describe convolutional codes a complete solution has been given [2]. Work is nearing completion for the general case.

References and Recent Publications:

1. B. C. Moore and L. M. Silverman, "Exact Model Matching by State Feedback and Dynamic Compensation", presented at the 1971 Decision and Control Conference, December 1971. Also to appear in the IEEE Transactions on Automatic Control.
2. B. C. Moore and L. M. Silverman, "A New Characterization of Feedforward, Delay-Free Inverses", presented at the 1972 International Symposium on Information Theory, Pacific Grove, Calif., January 1972.

3.1.4 Optimal Control Problems with Mixed Control - Phase Variable Equality and Inequality Constraints

A USC Project - No Contract Support

L. W. Neustadt

Objective:

To obtain necessary conditions of maximum-principle type for optimal control problems containing equality and inequality constraints involving both the control and phase variables.

Approach:

The problem was attacked from the viewpoint of a mathematical programming problem in Banach spaces with an equality constraint in an infinite dimensional Banach Space (L_∞).

Recent Progress:

Necessary conditions in the form of a maximum principle of the Pontryagin type were obtained for an optimal control problem containing ordinary differential equation constraints of the usual form

$$\dot{x}(t) = f(x(t), u(t), t), \quad t_1 \leq t \leq t_2,$$

phase inequality constraints of the form

$$p^i(x(t), u(t), t) \leq 0, \quad i = 1, \dots, \mu', \quad t \in I',$$

$$p^i(x(t), u(t), t) = 0, \quad i = \mu'+1, \dots, \mu, \quad t \in I',$$

where I' is a given subset of $[t, t_2]$. In addition, more conventional constraints of inequality type or the control variable

$$q^i(u(t), t) \leq 0, \quad i = 1, \dots, o, \quad t_1 \leq t \leq t_2,$$

as well as constraints on the initial and final values of x were also included.

The results obtained were similar to previous ones of other authors, but much weaker "compatibility" conditions on the q^i and the p^i were assumed in this study than was the case in the earlier work.

References and Recent Publications:

1. 1 paper completed and submitted to SIAM Journal on Control: "Optimal Control Problems with Mixed Control-Phase Variable Equality and Inequality Constraints", by K. Makowski and L. W. Neustadt.
2. Book - completed and submitted to publisher (Holt, Rinehart, & Winston): Optimization: A theory of Necessary Conditions, by L. W. Neustadt.

3.1.5 Simplified Filter Models

F44620-71-C-0007, The Joint Services Electronics Program

D. D. Swarder

Objective:

To derive algorithms which will provide near optimal filters with reduced computational requirements.

Approach:

The filters will be derived using projection methods developed in the earlier reporting period.

Recent Progress:

An algorithm has been derived for finding the best estimate of a linear function of the state variables of a linear system when a constraint is placed on the computational complexity of the estimator. Necessary conditions on the estimator dynamics have been derived. When the dynamic modes of the estimator are prespecified, a constructive method for finding the best filter has been given. Without this restriction a gradient search must be made in conjunction with the aforementioned method to find the true optimum.

References and Recent Publications:

1. "Optimal Sub-optimal Linear Filtering", C. B. Shortwell, Ph.D. Dissertation, 1972.
2. "Suboptimal Control of Linear Systems Derived from Models of Lower Order", 1971 Joint Automatic Control Conference, pp. 926-935, 1971; also AIAA Journal, Vol. 9, No. 8, pp. 1461-1467, August 1971 (with R. O. Rogers).
3. "Constrained Linear Filtering as a Multistage Process", 1971 Joint Automatic Control Conference, pp. 135-139, 1971 (with A. Jain).
4. "Feedback Estimation Systems and the Separation Principle of Stochastic Control", 1971 Joint Automatic Control Conference, pp. 834-840, 1971; also IEEE Trans. on Automatic Control, Vol. AC-16, No. 4, pp. 350-354, August 1971 (with S. C. Sworder).
5. "Optimal Control, Repair and Inventory Strategies for a Linear Stochastic System", 1971 IEEE Conf. on Decision and Control, pp. 393-394, 1971 (abstract); also IEEE Trans. on Systems, Man and Cybernetics, July 1972 (with T. Kazangey).

3.2 COMMUNICATION SYSTEMS

3.2.1 Nonparametric and Adaptive Techniques in Communication

GK 14190, National Science Foundation

NAS 5-21505, National Aeronautics and Space Administration

NGL-05-018-118, National Aeronautics and Space
Administration

L. D. Davisson

Objective:

To investigate and evaluate the performance of nonparametric and adaptive techniques in communication applications; to develop a practical data compression system for video data.

Recent Progress:

The effect of small sample sizes on rank tests has been investigated. It is found that rank tests perform nearly as well as the optimum detector for charge signals in Gaussian noise.

A continuous time RC filter-limiter-RC filter system has been examined. An important conditional mean linearity conjecture has been disproven.

The effect of dependence on adaptive filter performance has been partially evaluated when the dependence is confined to a finite time interval.

A real time data compression system has been developed and put into partial operational use for the transmission of video data between Wallops Island, Virginia, and Suitland, Maryland.

References and Recent Publications:

1. L. D. Davisson and R. L. Kutz, "A Real Time Programmable Data Compression System", Proc. Int'l Telemetry Conference, 1971.
2. L. D. Davisson, "A Survey of Data Compression", Proc. Allerton Conf. on Circuit and System Theo., 1971.

3.2.2 Graph Theory, Networks, and Mathematical Modeling
with Systems Engineering Applications

AFOSR 68-1555, The Air Force Office of Scientific Research

S. W. Golomb, I. S. Reed, H. Laiten and R. A. Scholtz

Objective and Approach:

To investigate the many new and continuing problems which are outgrowths of previous work under the general title of "Automata and Communications" with specific attention directed to three topics listed in the following section.

Recent Progress:

a. Coding Problems in Information Theory. Publications and lectures on this topic for the past three years include:

- 1) "Perfect Codes in the Lee Metric and the Packing of Polyominoes," by S. W. Golomb and L. R. Welch, SIAM Journal on Applied Math, vol. 18, no. 2, January, 1970, pp. 302-317.
- 2) "Algebraic Coding and the Lee Metric," by S. W. Golomb and L. R. Welch, Chapter 10 of Error Correcting Codes, edited by Henry B. Mann, John Wiley and Sons, 1969, pp. 175-194.
- 3) "A General Formulation of Error Metrics", by S. W. Golomb, IEEE Transactions on Information Theory, vol. IT-15, no. 3, May 1969, pp. 425-426.
- 4) "Tiling with Sets of Polyominoes," by S. W. Golomb, The Journal of Combinatorial Theory, vol. 9, no. 1, July 1970.
- 5) "Sphere Packing, Coding Metrics, and Chess Puzzles," by S. W. Golomb, presented to the Second Chapel Hill Conference on Combinatorial Mathematics and Its Applications, at the University of North Carolina, May 1970, and published in the Symposium Proceedings, August 1970.
- 6) "Combinatorial and Geometric Aspects of Coding," Research Award Address by S. W. Golomb to the University of Southern California Faculty, May 8, 1969.
- 7) "Geometry of Coding," invited address by S. W. Golomb to the National Telemetry Conference, April 27, 1970, Los Angeles, California.

- 8) "Information Theory and Coding," invited hour-address by S. W. Golomb to the SIAM meeting at Caltech, 24 April 1971.
- 9) "Efficient Coding and the Packing of Octahedra," invited talk by S. W. Golomb at the Seminar on Structure, USC, 4 May 1971.
- 10) "The Systematic Selection of Cyclically Equivalent Codes," by I. S. Reed and C. T. Wolverton, IEEE Transactions on Information Theory, March 1972.
- 11) "Notes on the Arithmetic BN Modulo A Codes," by I. S. Reed and A.C.L. Chiang, IEEE Transactions on Information Theory, to appear, 1972.

b. Analytical Foundations of Statistical Communication Theory. The articles contributing to the mathematical foundations of information theory and communication theory starting in 1970 are:

- 1) "The Lambda Method in Prime Number Theory," Journal of Number Theory, V. 2, N. 2, May 1970, pp. 193-198.
- 2) "A Class of Probability Distributions on the Integers," Journal of Number Theory, V. 2, N. 2, May 1970, pp. 189-192.
- 3) "Powerful Numbers," American Mathematical Monthly, vol. 77, no. 8, October 1970, pp. 848-852.
- 4) "A New Arithmetic Function of Combinatorial Significance," S. W. Golomb, accepted by the Journal of Number Theory, 1971.
- 5) "On the Survival of Sequence Information in Filters," by S. W. Golomb, IEEE Transactions on Information Theory, March 1972.
- 6) "An Information-Theoretic Measure of Image Similarity," by I. S. Reed and L. A. Liporace, to appear, IEEE Transactions on Information Theory, 1972.

c. Automata, Logical Design and Graph Theory. Publications on this topic since 1970 are:

- 1) "On the Enumeration of Finite State Synchronous Sequential Machines," USCEE Report 389, by I. P. Bottlik (based on Ph.D. dissertation supervised by I. S. Reed), June 1970.

- 2) "Error Tolerant Sequential Circuit Design Using Error Correcting Codes," USCEE Report 388, by R. W. Larsen (based on Ph.D. dissertation supervised by I. S. Reed), June, 1970.
- 3) "The Stability of Counting Sequences Under Stage Delays," by S. W. Golomb, jointly with M. Cohn, S. Even, and A. Lempel, The SIAM Journal on Applied Mathematics, vol. 20, no. 2, March 1971, pp. 183-188.
- 4) "K-th Order Near Orthogonal Codes," by I. S. Reed, IEEE Transactions on Information Theory, vol. IT-17, No. 1.
- 5) "Some Decompositions of the Integers from 0 to p^n-1 ," by S. W. Golomb, American Mathematical Monthly, February, 1972.
- 6) "Numbering the Nodes of a Graph," by S. W. Golomb, an invited chapter-length contribution to the book, Computing and Graph Theory, Academic Press, edited by R. C. Read, 1972.
- 7) "Graceful Graphs," Scientific American, March 1972, by S. W. Golomb.
- 8) "The Inner Product Computer," by E. E. Schwarzlander, Jr., USC Ph.D. dissertation supervised by I. S. Reed, June 1972.
- 9) "Coding Techniques for Failure-Tolerant Counters," by I. S. Reed and A.C.L. Chiang, IEEE Transactions on Computers, November 1970.
- 10) "Path Sensitization, Partial Boolean Difference, and Automated Fault Diagnosis," by I. S. Reed, A.C.L. Chiang, and A. V. Barnes, IEEE Trans. on Computers, February 1972.
- 11) "Redundancy by Coding Versus Redundancy for Failure-Tolerant Circuits," by I. S. Reed and R. W. Larson, IEEE Transactions on Computers, February 1972.
- 12) "Symbolic Design Techniques Applied to a Stored Microprogram Computer," by I. S. Reed, COMPUTER, May/June, 1972.
- 13) "Boolean Difference Calculus and Fault-Finding," by I. S. Reed, to appear, SIAM Journal.
- 14) "On-Off Digital Communications," by I. S. Reed and R. A. Scholtz, presented at Asilomar Conference (January 1972) and submitted for publication.

3.2.3 Frequency Tracking Study

F44620-71-C-0007, The Joint Services Electronics Program
DA-ARO-D-31-124, Army Research Office, Durham

C. L. Weber and R. L. Scholtz

Objective:

To determine the performance of approximate optimal estimators of frequency from the observation of a frequency modulated, fading signal in wideband noise.

Approach:

Use nonlinear recursive estimation theory to determine the estimator and simulator to check the real performance against performance of a linearized model.

Recent Progress:

This project is now completed with results published as reported below.

However, as an off-shoot of this study, examination was made of the performance of an on-off communications system, which required only frequency synchronization, i.e., not phase synchronization, in its mechanization. The results were reported at the IEEE International Symposium on Information Theory, Pacific Grove, Calif. (Jan. 1972) and submitted to IEEE Transactions on Communication Technology.

References and Recent Publications:

1. Dissertation: Thelma Rodriguez, "Frequency Tracking Loop Study", Ph.D., 1971.
2. T. M. Rodriguez, R. A. Scholtz, C. L. Weber, "Frequency Tracking Loop Study", Hawaii International Conference on Systems Sciences, Jan. 1972.

3.2.4 Signal Acquisition and Synchronization Studies

F44620-71-C-0007, The Joint Services Electronics Program
N00014, 67A-0269, Office of Naval Research

W. C. Lindsey

Objective:

To further develop the theory of signal acquisition and synchronization in the presence of noise and interference.

Approach:

To develop a signal acquisition theory including acquisition time, acquisition range and probability of acquisition in the time interval $[t_0, t]$ as a function of the system phase detector characteristic, loop filter and signal wave forms.

Recent Progress:

The transition probability density function, which statistically characterizes the phase error process in a first-order synchronization system, has been developed using the theory of continuous Markov processes. This statistical characterization has applications to establishing the fundamental limitations on performance of a sync system operating in noise. More recently, work has proceeded on the development of a theory which specifies the time to acquire a signal when the synchronization system has an arbitrary phase detector characteristic. Emphasis is placed upon second and third order sync systems. Some experimental work is expected when the new communication laboratory is established. Applications of the theory are applicable to design and planning of advanced communication, identification, navigation and command.

References and Recent Publications:

1. Book entitled, Synchronization Systems, W. C. Lindsey, manuscript completed, to be published June 1972.

3.2.5 Digital Image Enhancement Techniques

GK-2058, National Science Foundation

H. C. Andrews

Objective:

This study of digital transform image enhancement techniques has 3 main goals:

- a. An investigation as to the applicability of traditional analytic techniques resulting in orthogonal transformations to digital image enhancement. This would include super-resolution and Karhunen-Loeve principles for the deterministic and stochastic cases respectively.
- b. An investigation into the possibility of efficient implementation of general orthogonal transforms as suboptimum solutions to number 1 above.
- c. An investigation into the use of known, efficiently implementable transforms for image enhancement. Such transforms include the Fourier, Hadamard, generalized Walsh, Haar, generalized Haar, and a variety of other unnamed transforms, all implementable on the order of $pN \log_p N$ operations or less compared to the N^2 operations normally required. Here $p^n = N$.

Approach:

- a. Catalog characteristics and properties of existing transforms suitable for image enhancement.
- b. Investigate the structure of transformed images for specific classes of degraded images, with specific emphasis on low contrast images, using various transforms.
- c. Evaluate the image enhancement attainable by linear and nonlinear processing of transform samples for various transforms.
- d. Investigate potential algorithms and computational techniques for those image enhancement transforms with most significant promise.

Recent Progress:

Activity during the reporting period was directed to 2 topics:

- a. Image Processing Using Digital Computers. Recently digital computers have been brought to bear on the problem of processing natural quality imagery with surprising success. Optical processes,

communication systems, and automatic image detection are three areas of application for the computer techniques. Yet, perhaps the most exciting areas of research are those in which image restoration, enhancement and measurement are implemented through the power of the large scale general purpose digital computer. Details of our research can be found in the paper (7, below) designed to present a few of these areas of application in the hopes that the reader can get a general feel for the flavor and possibilities of combining the computer and natural images for processing purposes. Examples might include bandwidth reduction, detection, biomedical processing and pseudocolor. Probably the technique of digitally generated pseudocolor is in its most formative stages and applications are developed to illustrate a variety of examples from this relatively new field.

b. Nonlinear Intrinsic Dimensionality Computations. In the feature selection aspect of mathematical pattern recognition, the raw data and dimensionality of the measure space is usually very large. Therefore, some form of dimensionality reduction has been commonly considered as a practical pre-processing method. Based on one of previous methods, which increases the variance while maintaining the local structure a technique is developed to determine intrinsic dimensional structure.

The minimal spanning tree in the cluster is studied in order to tie it to the cluster structure. It has been proven that if the rank order is always maintained, a minimal spanning tree will not change its structure in the unfolding process. A cost function is introduced to guide the maintenance of the rank order. Two criteria of using the cost function to increase the variance have been introduced. The local structure is related to the connection on the minimal spanning tree. Several methods to define the local region are suggested. A program is implemented and tested to find the intrinsic dimensionality of the clusters. To date the technique has successfully unfolded helices, hemispheres, cubes, and lower dimensional surfaces imbedded in higher dimensional spaces.

References and Recent Publications:

1. "Data Compression and Enhancement of Sampled Images", with A. G. Tescher, Applied Optics, Vol. 11, No. 4, pp. 919-925 (April 1972).
2. "An Experimental Comparison for Karhunen-Loeve and Other Unitary Transforms for Feature Selection Using RDT", Hawaii International Conference on Systems Sciences (January 1972).
3. "Two-Dimensional Sequency Filters", with H. F. Harmuth and K. Shibata, IEEE Transactions on Communication Technology, June (1972).

4. "Image Display Enhancement and Maximum Entropy", with A. G. Tescher, Hawaii International Conference on System Science, January (1972).
5. "Performance Measures for Transform Data Coding", with W. K. Pratt and J. Pearl, IEEE Transactions on Communication Technology, June 1972.
6. "Digital Computers and Image Processing", Invited Paper, Endeavour, May (1972).
7. "Image Processing Using Digital Computers", (with H. G. Tescher, and R. P. Kruger), IEEE Spectrum (July 1972).

3.3 COMPUTER SYSTEMS AND AUTOMATA THEORY

3.3.1 Automata and Formal Language Theory

GJ-28787, National Science Foundation

S. Ginsburg, A. Gabrielian, D. Kiel, J. Outwater
and B. Rovin

Objective:

- (1) To develop suitable models of computer devices and software, and
- (2) to use the mathematical models to answer questions of interest to computer science.

Approach:

The method consists of studying various families of devices and formal languages, both in the specific and in the abstract.

Recent Progress:

In the work leading to the report of Reference 1, acceptors with nonlinear types of storage were studied. In particular, a model was introduced which is broad enough to encompass multitape AFA as well as devices with more exotic, but practical storage structure, such as trees, linked lists, two dimensional storage, etc. By appropriate recoding, it is shown that such acceptors still define AFL.

In preparing the report of reference 2, a class of grammars, called context-limited, which are weakly equivalent to the context free, were studied. These grammars may be viewed as the ones for which the scan limited automata are the parsing algorithm. It is shown that the unambiguous context limited grammar languages and the unambiguous context-free languages coincide.

During the report period, five papers (3-7) were published.

References and Recent Publications:

1. A. Gabrielian and S. Ginsburg, "Structural Storage AFA", submitted for publication.
2. T. N. Hibbard, "Context Limited Grammars",
3. S. Ginsburg and J. Hopcroft, "Images of AFL Under Certain Families of Homomorphisms", Math. Systems Theory, Vol. 5 (1971), pp. 216-227.

4. R. Book and S. Ginsburg, "Multi Stack Counter Languages", Math. Systems Theory, Vol. 6 (1972), pp. 37-68.
5. S. Greibach and S. Ginsburg, "Multitape AFA", Journal of Assoc. for Comp. Mach., Vol. 19 (1972), pp. 193-221.
6. J. Goldstine, "Substitution and Bounded Language", Journal of Computer and System Sciences, Vol. 6 (1972), pp. 9-29.
7. J. Guiliano, "Writing Stuck Acceptors", Journal of Computer and System Sciences, V 6 (1971), pp. 168-204.

3.3.2 Decomposition of Scenes Into Bodies Using Distance Functions

F44620-71-C-0007, The Joint Services Electronics Program

A. L. Zobrist and W. L. Thompson

Objective:

To develop algorithms or computer programs which calculate a "distance function" between parts of an image or picture which approximates human perception of distance. Gestalt clustering of parts into wholes can be performed using this distance function. This capability is needed for image processing and robot vision applications.

Approach:

Interactive computer graphics will allow rapid development and testing of programmed distance functions. Individual photoprocessing will allow accurate comparison with human perception. Application to real world scenes will follow.

Recent Progress:

In this new project, recent activities included the following. The interactive graphics program has been written and debugged. Seven elementary distance functions have been programmed. Informal psychophysical tests have been performed using linear combinations of these distance functions, and results show that this approach will work on simple scenes. One interesting result is that the orientation of small edges is a strong textural cue for the decomposition of scenes into bodies. A graduate student is presently adapting this work for application to real world scenes.

3.3.3 Hardware Implementation of Operating Systems

F44620-71-C-0007, The Joint Services Electronics Program

R. Card

Objective:

To study the implementation in hardware of the functions of the operating system of a computer.

Approach:

Microprogramming will be used to achieve the desired hardware control.

Recent Progress:

Various tasks of an operating system have been studied with the object of determining how they might best be implemented or augmented by microprogrammed routines and what the advantages are of microprogramming over conventional implementation techniques. These tasks include scheduling and allocation of resources, file operations, intercommunication and control of application programs, and interrupt service routines.

Microprogrammed routines have been designed to implement the control and intercommunication of parallel processes. The design is based on theoretical studies that have appeared in recent publications by several authors. The usefulness of the microprogram implementation of an algorithm for parallel process control and communication is in the reduction in the amount of main memory used by the operating system and the increase in the speed of execution of the algorithm.

In order to further study the performance of microprogrammed routines designed in this research, a microprogram simulator has been installed on the university's 370/155 computer system. Further research will continue under other contracts with the goal of studying, under simulated execution, the operation of designs for the microprogrammed implementation of various tasks of an operating system.

3.3.4 Computer Program Translation

N00014-67A-0269-0020, Office of Naval Research

P. Gilbert

Objective:

To obtain formal models of syntactic analysis and translation which include parsing schemes as explicit components which are adequate (in a strict formal sense) for the parsing and translation of actual programming languages, and which can be "carried into practice" to yield rigorously based but efficient translators.

Approach:

To extend previous work wherein models called the analytic grammar and the analytic transducer were developed and their properties were studied.

Recent Progress:

Technical Report No. 1 obtains classes of grammars which are adequate for the parsing, and classes of transducers which are adequate for the translation of actual programming languages. Subsequent work has emphasized the "carrying into practice" of these models.

Specifically, a construction has been developed for a Turing machine parser. This construction exactly parallels, in certain important respects, the construction of syntax tables (or segments of program) of actual parsers. This construction has been shown to be especially amenable to minimization. Measures of efficiency have been outlined for this parser, and related to the efficiencies of actual parsers. Some simple minimization techniques have been outlined.

References and Recent Publications:

1. Technical Report No. 1: "Syntactic Analysis and Translation of Programming Languages," December 1971. (Revised version also submitted for publication to the Journal of the ACM)

3.3.5 Synthesis of Sequential Machines

F44620-71-C-0007, The Joint Services Electronics Program

R. S. Kashef

Objective:

To provide a set of functions which can synthesize a large class of sequential machines that are of minimal complexity and can be easily fault tested and corrected.

Approach:

To consider the synthesis problem as a class of four sets of transformations. $T_{(1)}$, $T_{(2)}$, $T_{(3)}$ and $T_{(4)}$, with each element of the class consisting of $t_{(1)} \times t_{(2)} \times t_{(3)} \times t_{(4)}$ where $t_{(i)}$ is an element of $T_{(i)}$ and $T_{(1)}$ transforms a given problem into the equivalent minimum flow table, $T_{(2)}$ provides the state equations for the given problem and $T_{(4)}$ provides the minimum cost equations based on the given technology.

Recent Progress:

Significant results have been accomplished toward the evaluation of $T_{(2)}$, with the immediate result being that APC codes can be used to code any flow tables up to 16-rows of sequential machine and n-rows of flow tables with maximal partitions. These codes are $n + \log_2 n$. Toward the overall synthesis problem, synthesis in cellular spaces are being studied with partial results indicating that Bank's cellular space seems to be universal and Shoup's cellular space is not practical for synthesis. New spaces are being investigated both for universality and practical simplicity, specifically those made up of functions of 2 variables. Also, synthesis of sequential machines in cellular space of less complexity (fewer states) are being investigated.

References and Recent Publications:

1. "A Formal Approach to the State Assignment of Asynchronous Sequential Machines", IEEETC, Computer Group Repository R-71-159, Nov. 1971.
2. "On the Race-Free Assignments and Classifications of 9 to 16 Rows Asynchronous Sequential Machines", IEEE TC Computer Group Repository R-71-158, Nov. 1971.
3. "On the Race-Free Assignment and Classification of Asynchronous Sequential Machines", Proceedings of the 5th Hawaii International Conference on Information and System Sciences, Jan. 1971.

4. "Augmented Parity Check Codes for Encoding of Asynchronous Sequential Machines", Revised Nov. 1971 for IEEE TAC, accepted for publication.

3.3.6 Generation of Fault Detection Tests for Intermittent Faults in Sequential Circuits

F44620-71-C-0067, The Joint Services Electronics Program
N00014-67-A, 0269-0019, Office of Naval Research
GK-23886, National Science Foundation

M. A. Breuer

Objective:

- a) To determine models for intermittent faults in digital circuits;
- b) To determine an effective procedure for generating tests for detecting these faults;
- c) To analyze the statistical properties of detection of intermittent faults.

Approach:

To model the time domain into a space dimension. Single intermittent faults in the time domain (faults that come and go) are thus mapped into multiple solid faults. Models will then be developed for pattern sensitive faults which occur in devices such as dynamic RAM memories. Models for delay induced faults will also be developed.

Recent Progress:

The appearance of an intermittent failure is often due to reasons other than signal line values. For these failures a statistical model independent of circuit input and state can be used. In this research, one such model was introduced based upon Markov chains. Some of the statistical properties of detecting intermittent faults were then investigated. A concept of a fault pattern was introduced for characterizing when a fault pattern was introduced for characterizing when a fault is present, and in which permanent faults and the fault free situation are included in special cases. Hence, the model is a significant generalization of previous work. We have shown that, in general, no single test sequence will detect all possible fault patterns. We have shown how to calculate the probability of detection of a test sequence. We indicated a procedure, based upon the d-algorithm, for constructing a test for an intermittent

failure. We show that the behavioral effect of an intermittent failure on a circuit may be to increase the number of states in the circuit.

References and Recent Publications:

1. "Generation of Fault Detection Tests for Sequential Circuits", M. A. Breuer, Digest of 1971 International Symposium on Fault-Tolerant Computing, March 1-3, 1971, pp. 18-21.
2. "An Algorithm for Generating a Fault Detection Test for a Class of Sequential Circuits", M. A. Breuer, Theory of Machines and Computations, Academic Press, 1971.
3. "A Random and an Algorithmic Technique for Fault Detection Test Generation for Sequential Circuits", M. A. Breuer, IEEE Trans. on Computers, V C-20, N11, pp. 1364-1370, November 1971.

3.4 ELECTRIC POWER SYSTEMS

3.4.1 Intermediate Term Load Forecasting

P. O. 20238, Los Angeles Department of Water and Power

J. Lamont

Objective:

Investigate presently accepted techniques for load forecasting and report which would have been most accurate for the Dept. of Water and Power. Determine the significance of various factors and make a final forecast.

Approach:

Use extrapolation and regression techniques to forecast future electric loads.

Recent Progress:

Data has been gathered relating to economic, geographic and climatic conditions in Los Angeles. Studies are now in process to determine how these conditions effect the electric demand.

4. MATHEMATICAL BIOSCIENCES AND BIOMEDICAL ENGINEERING

4.1 Mathematics in Biology and Medicine

GM 16197-05, Department of Health, Education and Welfare

GP 29049, National Science Foundation

AT (04-3)-113, Atomic Energy Commission

R. Bellman, E. Angel, S. P. Azen, J. Buell, A. Jain,

R. Kalaba, B. G. Kashaf, A. Jain, C. Kell, M. J. Merritt,

S. Osaki, S. Ueno, R. Vasudevan

Objective:

In engineering, mathematics has repeatedly furnished the conceptual and analytic mechanisms for the design and effective operation of major systems. It has been clear for some time that we must pursue a similar program in the study of biological and medical phenomena. The human body has the ability to maintain homeostasis, to perform complex actions like walking and talking, seeing and hearing, to operate a brain which stores and retrieves data and makes decisions, and finally to reproduce itself. All of these activities represent feats of astounding dimension. Most defy complete explanation at the present time despite the enormous effort devoted to their study. Even partial understanding, however, will have wide-ranging consequences with rewards to society which will dwarf all previous contributions of science.

A basic part of the challenging set of problems that faces us then is that of combining modern technology, as represented for example, by computers and radiation physics, with modern mathematics to study the multiple questions involved in the prevention and cure of illness, in patient care, and in the education and training of medical and paramedical personnel as well as research personnel.

Approach:

In the many research papers produced in this program, we have repeatedly indicated how even simplified versions of medical processes lead quickly to quite intricate mathematical equations. Conversely, we have described how the abstruse mathematical problems we have treated

arise from specific diagnostic and therapeutic questions, and have, in many cases, immediate application.

Initially, it is perhaps surprising to people that the human body should produce mathematical complications which so often greatly surpass in difficulty the familiar glamorous problems of the world of physics and engineering. Because of familiarity with body processes we tend to ignore their complexity, and assume that physiological processes, if not actually simple, are at least capable of simple treatment using familiar methods. Unfortunately, this is not the case.

It is only when we attempt to produce the numbers required for the many decisions in medical treatment that we begin to appreciate the true complexity of the processes of biology and medicine.

Recent Progress:

The following paragraphs provide a survey of the broad areas of interest to this research group and the highlights of recent accomplishments.

a. Pharmacokinetics and Chemotherapy

As the result of pioneering research by a number of distinguished physiologists, Teorell, Kruger-Thiemer, Grodins, Jacquez, Segre and others, it is well established that there now exists sufficient physiological understanding to permit the construction of useful mathematical models of the distribution of specific drugs in the human body. In the standard fashion these models can be used to test and develop physiological concepts as well as to guide experimental procedures. Such mathematical models form the foundation for intensive investigations of cancer, viewed as a control, or rather, out-of-control, process, and other fundamental processes and, more generally, will provide the basis of one of the new fields of the future--mathematical physiology.

An important application of pharmacokinetics is to the field of chemotherapy, in particular, to the avoidance of "side-effect" reactions of prescribed drugs such as antibiotics, kanamycin and others, or digoxin. The problem may be viewed as that of providing adequate concentrations of the drug at a particular site in the body without having undesirable amounts at another site. We have shown that quite simple compartmental models can be used to good avail in the administration of digoxin, kanamycin, and gentamycin; the joint work of J. Buell and Dr. R. Jelliffe of the USC Medical School should be referred to for detailed results.

This activity in pharmacokinetics is being developed into a major program, working closely with USC Medical School faculty, Dr. R. Jelliffe and Dr. R. Maronde and his group. Both simple and complex mathematical and physiological models are being employed.

Computer programs for suggested dosage regimens based upon drug kinetics are concurrently being used clinically through computer terminals

located at the Los Angeles County USC Medical Center, and other centers as well; see below. These programs include those for the cardiac glycosides; digitalis, digoxin, digitoxin--including the metabolism of digitoxin, and ouabain. Concurrently, we are adding our latest computer models for use in antibiotic therapy for kanamycin and gentamycin which includes an inner ear compartment. Here the side effect is deafness.

An integrated research program on therapy using these drugs under the supervision of Dr. R. Jelliffe is currently being undertaken at the LACH-USC medical facility, approved by the Research Council of the Department of Medicine. Volunteer patients are being used in a controlled hospital situation in order to validate computer-predicted serum level results with actual patient data.

b. Nuclear Medicine

In this area there are many important problems connected with both diagnosis and therapy, as well as many in the domain of operations research. One task is that of providing the physician with information concerning the presence and nature of a tumor, as well as of other abnormalities of an organ; a second is that of providing him with techniques for treating the tumorous condition. Both can involve the use of radiation.

We know that early warning of cancer plays a vital role in successful treatment by means of surgery, radiology, and chemotherapy, all possibly combined in various ways. This means that vast screening programs are required for minimally effective mass medical care. Valuable data can be obtained at the present using radioisotopes and scanning techniques. However, there are still numerous problems connected with the gathering and use of these data as well as with the efficient operation of giant programs of this nature. Questions of display of data and information become significant here. Statistical ideas and dynamic programming can be effectively used; the biostatistics-side of this work has been performed by the Friedland-Ueno-Vasudevan group.

Let us briefly view some questions of therapy. In connection with the use of radiotherapy, it is essential to study the effects of radiation upon the human body. Once again, the side-effect problem is crucial. It is vital to ensure that the treatment does not harm the patient in the course of attempting to alleviate the original condition--the same problem is faced in chemotherapy.

Since the human body consists of a set of inhomogeneous masses of irregular shape, the mathematical problems involved in ascertaining and controlling the effects of radiation are severe. Fortunately, our group possesses the advantage of a base of years of extensive research in astrophysics, transport theory, and nuclear physics, as well as the help of a number of distinguished experts in experimental and theoretical aspects of these areas; Professor S. Friedland, Professor R. Vasudevan,

and Professor S. Ueno, to cite a few. Invariant imbedding plays a major role here, as well as various other methods for solving integral equations and nonlinear equations.

We are working closely with Dr. Siemsen at the USC Medical School, as well as with Dr. George's group in the Department of Radiology, LACH, and will actively pursue a number of other directions in radiotherapy.

We have continued the work on the identification problem in cardiology, started some years ago with Drs. Collier and Selvester. Now that we have developed a powerful new mathematical technique in the theory of identification, differential quadrature, we intend to expand considerably the scope of the previous work built upon the basic physiological results of A. Scher.

Research in neurophysiology involving cooperative effort of Dr. G. Moore of the Department of Electrical Engineering of USC, H. Sugiyama and S. Osaki has been continued and expanded. Again the newly developed technique of differential quadrature plays a significant role here.

Work on large, complex control systems, with particular application to orthotics and prosthetics and stroke, has been continued and expanded. The development of parallel processing computers, (ILLIAC), may be the breakthrough required to make some existing ideas operational.

c. Information Analysis

This is a vast area which includes the major problem of making readily available to the physician the information he requires for effective decision-making. In order to make fruitful use of a limited supply of medical professionals, we wish to provide a variety of computer screening techniques based upon statistical and mathematical techniques, such as analysis of electrocardiograms and phonocardiograms, of tissue smears, and so on, as well as a number of new techniques for the display of data using computer graphics.

This work is headed by S. Azen. Data are presented in one of many forms (e.g., histograms, scattergrams, etc.) on a CRT tube; subsamples are selected, manipulated, and analyzed. The researcher makes decisions along the way. Existing graphics and statistics programs (e.g., the BMD package) will be utilized. Closely tied in with this is the task of developing a "biostatistics language": a language, simple to learn, that performs statistical manipulations. For example, "REGRESS Y ON X" performs a simple linear regression.

A package of examples has been prepared which illustrates statistical concepts. This can be used as a valuable device to teach statistical techniques to medical people. A simple version is currently being used in teaching dental students at UCLA. In preparation is a somewhat more sophisticated package which explains sampling--random or stratified, the likelihood ratio procedure, maximum likelihood estimation, and so forth. Also under consideration are the application, extension, and

comparison of graphic procedures based on non-parametric Fourier estimates of probability densities, cumulative distribution functions, survival curves, etc.

Pattern recognition in general remains a stubborn field requiring a continuing effort. Despite its difficulty, it cannot be shunted aside since many kinds of pattern recognitions are absolutely essential for a health program for a nation of 200,000,000. A great deal can be done in connection with the identification of systems, as we shall indicate below. We expect that the parallel processing computer, such as ILLIAC-4 cited above, will allow dynamic programming to be used fruitfully in these areas.

The modern theory of statistics, combined with computers, is essential for the storage and retrieval of data required for large-scale patient care. This is an essential part of the study of large health systems.

All of this represents a sustained effort to analyze and improve the uses of computers in a hospital environment. It is part of a systematic program begun six years ago in conjunction with Dr. R. Maronde of LACH. We are also concerned with the training of the operators of computers and computing systems as well as the design of college curricula for these purposes.

We have emphasized decision-making as an essential part of medical care. Decision-making involving quantitative effects, and thus numbers, can be handled by various traditional mathematical methods. However, medicine involves people, and thus human values. These cannot be treated wholly by numbers, a fact which renders decision-making in medical areas very much more difficult than engineering decision-making. In the operation of medical systems, however, we cannot avoid these more difficult problems, nor those connected with general man-machine systems. On-line decision-making plays a vital role here. We refer below to the use of simulation techniques we have developed to study these types of questions, making significant use of the computer in this activity. C. P. Kell is in charge of these areas, aided by consultants Dr. W. C. Hopgood of UCLA, a practicing psychoanalyst, and Professor L. Zadeh of the Department of Engineering of the University of California at Berkeley, who is applying his new theory of fuzzy sets. There are many important applications to psychotherapy, both conceptually and operationally.

e. Hospital and Community Clinic Administration

In this area we apply operations analysis and system analysis techniques to the many problems arising in the areas of scheduling, communication, and organization. Many of these can be adequately treated by a combination of conventional mathematical theory and simulation. Dimensionality problems are severe, but again we expect that dynamic programming ideas will become much more effective with the new parallel-processing computers. S. Osaki has been working actively in these areas.

We are fortunate in being connected with Resthaven, a community mental health facility of moderate size, in the study of various problems involving the delivery of health services to the community, working closely with Dr. J. Krofcheck, Clinical Director, and his staff.

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4.2 Biomedical Engineering Program

GM16437, Department of Health, Education, and Welfare

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Objective:

To study a wide range of basic and applied problems in biological dynamics, control and communication. The specific fields of interest are the respiratory, cardiovascular, fluid-electrolyte, neural, and metabolic systems.

Recent Progress:

Only a brief summary of major accomplishments is presented here. Details can be found in the references.

a. Respiratory System

We have studied problems in respiratory mechanics, cycle optimization, chemical control, and the hyperpnea of exercise. In the area of mechanics, we have explored the mechanisms limiting maximum expiratory flow rate. Most previous analyses of this problem have treated airway impedance in terms of "tubes" whereas in reality the tracheobronchial tree is largely a collection of "junctions" connected by segments so short as to hardly qualify as tubes. By a more rigorous application of aerodynamic flow theory to a more realistic tracheobronchial flow net, we have shown that the phenomenon of "selective merging" at the junctions can account for 55% of the change in impedance during the expiratory flow maneuver. A probable cause of the remainder is junctional rather than tubular distortion, but this remains to be proven.

We have explored the possibility that the mechanical respiratory system is regulated in a way which minimizes the work required to produce a given level of alveolar ventilation. This hypothesis was tested by analytically predicting optimal airflow patterns and comparing these to experimentally measured patterns available from the literature. Good agreement was found with many animal patterns and human patterns observed under stress conditions. Human airflow patterns at rest, however, could not be explained by this hypothesis. Instead, a criterion of minimum mean-squared volume acceleration was found to predict airflow patterns which match the resting human pattern. This criterion can be linked to gas transport efficiency.

In the area of chemical control, we have explored the role of peripheral

and central receptors in the ventilatory responses to acute metabolic disturbances in acid-base balance. The responses of nembutalized dogs to infusions of 0.5 M HCl or 7% NaHCO₃ were studied with the carotid bodies intact or denervated and with $P_A(\text{CO}_2)$ clamped constant through servo-control. It was concluded that both peripheral and central receptors contribute to the ventilatory responses under these conditions.

That both receptors also contribute to the ventilatory response to sinusoidally varying $F_I(\text{CO}_2)$ in man has been supported by a computer simulation study. Using the mathematical model of Grodins, Buell, and Bart (1967), the responses to sinusoidal $F_I(\text{CO}_2)$ for several alternative controller hypotheses were explored, and then compared with experimental data in man taken from the literature (Bellville, 1969; Stoll, 1969). The best agreement was achieved when the controller equation included both a central and peripheral drive. This study also revealed that simulated responses to a sinusoidal $F_I(\text{CO}_2)$ input were much more sensitive to the form of the controller hypothesis than were responses to the more conventional step input.

To help resolve the mystery of exercise hyperpnea, we have done some preliminary studies on the ventilatory responses to dynamic $P_a(\text{CO}_2) - P_a(\text{O}_2)$ patterns associated with the respiratory cycle. A new technique was developed to provide a positive inspired CO₂ load and a "negative" inspired O₂ load which were independent of ventilation. That this procedure should produce $P_a(\text{CO}_2) - P_a(\text{O}_2)$ dynamic patterns similar to those of exercise was supported by a simulation study. Preliminary results in dogs indicated that the ventilatory response to this form of CO₂-O₂ loading resembles that to exercise. Recent results on work in this area can be found in References a, b, c and d.

b. Cardiovascular System

We have studied the baroreceptor reflex in the fetal lamb, developed and applied a frequency response method for the measurement of peripheral vascular parameters, and developed a promising non-invasive method of estimating cardiac output from respiratory measurements.

The baroreceptor study was an extension of previous work carried out prior to the initiation of this program in which a mathematical model of the isolated, uncontrolled "cardiovascular plant" of the fetal lamb was developed. In the present study, the model was extended by adding a baroreceptor control loop. The two major physiological questions asked in this study were (1) does a baroreceptor reflex exist in the fetal lamb? and (2) if it does, what plant parameters does it operate on? Model simulations were compared with experimental data provided by Assali and Brinkman working at UCLA. It was concluded that a baroreceptor

reflex does exist, and that it must operate in part upon the conductance of the placental circuit (References e and f).

We have developed and applied a frequency response method for the measurement of mechanical and exchange parameters in the peripheral vascular bed of the dog. In this method, a small amplitude sinusoidal volume forcing is introduced at the arterial end of an isolated perfused hind-limb kept under isogravimetric conditions. The responses of arterial and venous pressures, which are also sinusoidal, are recorded and the procedure is repeated over a range of frequencies. Using these frequency response curves in conjunction with a mathematical model of the peripheral vascular bed, it is possible to obtain numerical values for seven parameters simultaneously. Thus arterial, venous, capillary, and tissue compliances, as well as pre- and post-capillary resistances were measured under a variety of conditions (carotid sinus stimulation, sympathetic stimulation, transfusion, epinephrine infusion) (Ref. g). A seventh parameter which has the dimensions of a resistance or conductance, may or may not be related to a capillary filtration coefficient. This point is under further study at present (References h and i).

The parameter estimates mentioned above were based on a linear, lumped element model which assumed uniform tissue and capillary compartments. However, a CFC (capillary filtration coefficient) gradient has been reported from the arterial to the venous end of capillaries. Also, a hydrostatic gradient is known to be present along the capillary length. The impact of these characteristics on the estimate of a single CFC value was studied by computer simulation. It was found that gradients of CFC and pressure do not have significant effects. The estimate of a single CFC merely reflects the average CFC along the capillary length (Ref. j).

While the frequency response method yields useful parameter estimates, its main disadvantage is the lengthy experimental period required to collect the necessary data. Up to one half hour of data are required during which stationarity of the preparation may be a problem. We have evaluated several alternative methods of estimation in an attempt to shorten the time required. Computer simulation results indicated that a modulating function approach was the most promising (Reference k).

We have developed a non-invasive method for the measurement of cardiac output using only respiratory measurements and a mathematical model of the respiratory system. It is based upon the fact that cardiac output is a parameter of the respiratory system. A mathematical model of this system (Grodins and James, 1963) is simulated on a computer and forced (on-line) with a signal proportional to the subject's total ventilation. The output of the model is a signal representing end-tidal P_{CO_2} . This computer generated $P_{ET}(CO_2)$ is compared with the subject's $P_{ET}(CO_2)$ as measured with a Beckman CO_2 analyzer. A criterion function is formed by squaring the difference between these two signals at the end of each breath and minimized by adjusting the model cardiac output using

a discrete steepest descent procedure. The method was tested in ten anesthetized dogs using the cardiogreen dye dilution technique as the primary standard of comparison. Model and dye estimates agreed within 10% for all experiments over a three-fold range of cardiac output. Over half of the estimates agreed within 4%.

c. Fluid-Electrolyte Studies

Studies in this area have been concerned with renal hemodialysis, dynamic interchanges of water and solutes between fluid compartments, and the renal regulation of bicarbonate balance.

1. Renal hemodialysis. We have conducted investigations designed (1) to predict changes in body chemistry during artificial kidney (hemodialysis) treatments, (2) to optimize artificial kidney treatment in the sense of removing maximum amounts of chemical substances in a given time without producing gross imbalances in body chemical distributions, and (3) to quantitatively describe the dynamic and steady state rates of chemical removal by the artificial kidney machine.

To aid the clinician in his prescription of artificial kidney treatment for an individual patient, we devised mathematical models which could accurately predict body fluid concentrations of urea and creatinine in a given patient knowing only his weight and the average blood flow into the kidney machine. The results were used to generate nomograms (1) from which the physician can rapidly make estimates of concentration changes for a given patient under treatment.

We have done some theoretical studies on maximizing the rate of removal of urea from a patient while maintaining transcellular concentration gradients below specified levels. Presumably the maintenance of small concentration gradients would prevent the occurrence of the "Disequilibrium Syndrome" which comes about during rapid dialysis in patients. Those studied showed that the method of dynamic programming could be used to specify optimum removal rates under these constraints.

In conjunction with the above studies, we have developed mathematical descriptions for the removal of chemical substances from the body by the artificial kidney (m). A transient analysis of these devices may prove important in studying the chemical changes in a patient during the initial minutes of hemodialysis where the blood flow is not constant and the chemical concentrations in the patient's blood are most rapidly changing.

2. Dynamics of Compartmental Exchange. We have constructed a mathematical model describing the dynamic interchanges of water and solute in an animal or human following rapid infusions of chemical solutions or other perturbations. The model uses the compartmental concept and considers fluid interchanges between red cells, plasma, interstitial fluid and intracellular fluid to result from pressure and concentration differences between these fluids as well as from solvent-

solute coupling (see Reference n).

Since the model includes the whole body rather than a single isolated perfused organ or tissue, the parameters are, for the most part, determined indirectly by fitting to experimental data. It has thus been necessary to devise methods to measure a sufficient number of variables in the experimental animal to permit reliable estimates of these parameters. In particular, methods for measuring plasma volume dynamics were investigated (o). Two independent methods were used. The first depends upon the disappearance curve of radioactive albumin from the circulation, and the second upon dynamic measurements of red cell volume and hematocrit. Although each of the methods had been previously suggested in the literature, they had never been used simultaneously or during rapid transients.

Both methods gave very similar results for the transient responses of plasma volume after fluid infusion. These data together with transient changes of red cell volume and chemical concentrations have been used to establish whole body parameters for the model. We are currently evaluating the variance of these from animal to animal, as well as comparing them with estimates derived from isolated organ experiments.

Models such as this can ultimately be used to assess the effects of fluid infusions and losses in human patients.

3. Renal Control of Electrolyte Balance. We are currently conducting experiments to determine the most important factors responsible for the renal regulation of bicarbonate balance. In this current work we have centered our attention on the renal reabsorption of the bicarbonate ion, since it is through this process that the fine control of excretion is achieved.

Previous workers have implicated a number of factors in the modification of bicarbonate reabsorption. These are: the plasma concentrations of hydrogen, bicarbonate and potassium ions; P_{CO_2} ; ratio of the reabsorbed to the filtered sodium; and the extracellular fluid volume (ECF). In all previous work, the changes in reabsorption due to a number of these factors were studied, and in every case the ECF was expanded in order to increase plasma bicarbonate concentration above the "renal threshold" as defined by Pitts and Lotspeich. Thus, the observed bicarbonate changes were always associated with simultaneous variations in a number of potential causative factors, and the individual effects of each could not be separated. Our experiments are unique in that we have raised plasma bicarbonate levels without expanding ECF. This was accomplished by exchange hemodialysis with an artificial kidney machine. The results indicate that ECF expansion is a primary but not the sole factor in the depression of bicarbonate reabsorption at high levels of plasma bicarbonate concentrations.

d. Neuronal Signals and Systems

There are four principal areas of work that have been under active research since the beginning of the program project grant.

1) Much work, especially in the early period of the grant, was spent completing a study of the basic theory and applications of a technique for the extracellular detection and characterization of synaptic interactions between neurons. The basic approach assumes that when two neurons are synaptically connected, the firing probability of the postsynaptic cell will be influenced by activity in the presynaptic cell, especially after short delays during which a postsynaptic potential appears. The technique depends on the calculation of the crosscorrelation histogram for the two cells, and we showed based on earlier studies (Moore, Perkel, Segundo, Gerstein, 1966, 1967) that the specific features of the crosscorrelogram reflected the existence as well as the amplitude, waveform, and polarity of the postsynaptic potential, and, in addition, reflected the statistical features of the firing pattern of both the pre- and post-synaptic cells and other neurons involved in the interaction. These techniques are now being used routinely in many studies conducted by other laboratories, as well as our own.

2) In connection with these studies, we continued to apply general statistical computer techniques to the study of single and multiple spike train records. In one study, we used auto- and crosscorrelation to characterize patterns of activity in single chemoreceptor fibers of the cat carotid body, and to show that these fibers exhibit a pronounced rhythmicity at the respiratory period and possibly a smaller cyclic pattern synchronous with the cardiac cycle. These techniques are now being extended to studies of the mechanism of transmitter release at the neuromuscular junction. Reference n relates to this work.

3) As a result of these investigations, it became clear that some more powerful methods of analysis, modeling and simulation of neuronal systems would be desirable. We therefore developed a powerful computational program for analysis and simulation of small neuronal networks so that the behavior of experimentally recorded cells and their simulated counterparts could be compared directly by statistical analysis. The unique feature of this system is that it was designed so that the parameters of the simulation program could be optimized with respect to the experimental data; this is not generally available and gives us enormous power in testing and validating proposed models of neuronal processes. Preliminary reports of this work have been made and will appear in extended form in several forthcoming papers.

An additional development has been the mathematical solution of a general class of mathematical models for neuronal spike train activity. This work allows the determination of general constraints on the parameters of an observed neuron and will be the cornerstone of a

generalized computer program which can identify neuronal parameters from an observed interval histogram.

4) Finally, we are presently conducting a number of studies whose aim is the development of more powerful and accurate models of single neuron processes. In particular, we are presently investigating models for the sodium pump, for transmitter synthesis and release, and have developed a general ionic flux model of the membrane, which, when combined with the Hodgkin-Huxley equations can account for an entire spectrum of passive sub- and suprathreshold behavior of a neuron (Reference q).

e. Metabolic and Endocrine Systems

This is the newest component of our research program, having only been underway since about the middle of 1970. Nevertheless, considerable progress has been made towards achieving the long term goals of this division. These goals include (1) the characterization of the organ system dynamics of liver, pancreas and adipose tissue in response to hormonal and substrate signals, (2) the definition of glucose and fatty acid (power) fluxes in the blood of unanesthetized animals as they adopt various metabolic states, (3) the identification of the corresponding informational fluxes associated with the power fluxes identified in (2) above.

For the study of organ system dynamics, highly reliable, computer controlled perfusion systems have been developed and tested using the "pilot organ" approach. Since these are described in detail in the body of the proposal (pp. 172-176 for fat; pp. 179-182 for liver; pp. 191-193 for pancreas), they need not be discussed further here. Some preliminary results using the pilot pancreas have recently been reported (r). In this study, temporal patterns of insulin secretion rate from the pilot pancreas in response to well-defined variations in the pancreatic arterial concentrations of glucose and amino acids were determined. The results indicated that glucose and amino acids stimulate insulin secretion by distinct mechanisms and demonstrated the dependence of the amino acid stimulated response on arterial glucose concentration.

In addition to these studies on isolated perfused organs or tissue, changes in both power fluxes (glucose and free fatty acids) and information fluxes (insulin) have been studied in conscious dogs. Some details of these studies are described on pp. 197-198 of the proposal, and some preliminary results have recently been reported (s). In the latter, temporal patterns of arterial plasma glucose concentrations during the resting state and during steady glucose infusions were studied in fasting conscious dogs over periods of thirty minutes to 11 hours. The results suggested that the glucose regulatory system may enter an oscillatory mode when stimulated by moderate infusions of glucose, but that this mode may not be detectable at rest or during low rates of infusion.

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- s. Marsh, D. J., M. Ookhtens, R. N. Bergman, and F. E. Yates, "Fluctuations of the Glucose Concentration in Arterial Plasma of Unanesthetized Dogs, With and Without Steady Infusions of Glucose," 3rd Annual BMES Meeting, Abstract 61, 1972.